

Fuel Treatment and Prescribed Fire



Fire Severity and Intensity During Spring Burning in Natural and Masticated Mixed Shrub Woodlands

Tim Bradley¹, Jennifer Gibson², and Windy Bunn³

Abstract—Fire risk is an ever present management concern in many urban interface regions. To mitigate this risk, land management agencies have expanded their options beyond prescribed fire to include vegetation mastication and other mechanical fuel treatments. This research project examined fire severity and intensity in masticated and unmanipulated units that were burned in spring in a Northern California mixed shrub woodland. Mastication treatments significantly altered the fuel profile, resulting in an approximate 200 percent average increase in woody fuel cover for 1-hr and 1000-hr TLFM size classes, and greater than 300 percent average cover increase in 10-hr and 100-hr TLFM size classes. The mean flame length (29 vs. 10 inches/ 74 vs. 25 cm) and flame zone depth (20 vs. 6 inches/ 51 vs. 15 cm) were significantly greater ($P<0.001$) in masticated units than in unmanipulated units as were the mean temperatures at the litter surface (657°F vs. 219°F/ 347°C vs. 104°C) and 1.64 ft (0.5 m) above the litter surface (277°F vs. 59°F/ 136°C vs. 15°C) ($P<0.001$). Greater flaming and heat release in the masticated units led to increased mortality of overstory and pole-sized oaks and conifers posing conflicts with the management objective of retaining overstory vegetation.

Introduction

Land managers in the Western United States are increasingly faced with the challenge of implementing wildland fuel reduction treatments that are both effective and achievable within reasonable time frames. Traditionally, managers have relied on prescribed fire as the primary tool for landscape level risk reduction and ecosystem restoration in fire prone plant communities. However, a number of challenges complicate the achievement of fuel reduction goals using prescribed fire alone. These challenges include air quality restrictions, limited burn windows, insufficient staffing, and the liability associated with escaped burns. Due to these limitations, managers are increasingly turning to the use of mechanical treatments as a supplement to prescribed fire for the accomplishment of fuels management objectives.

One option that has gained popularity with land managers in Western states is vegetation mastication, which can allow managers to quickly and safely decrease shrub and other understory vegetation at a fraction of the cost of comparable manual thinning treatments. Tens of thousands of acres of shrubs and other understory species in fire-prone plant communities are being treated with vegetation mastication to reduce fire hazard. Most land management agencies prefer to leave masticated biomass on the ground to cycle nutrients, prevent soil erosion, and to impede the establishment of non-native and invasive plant species. However, since mastication does not remove

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

¹ Fire Ecologist, National Park Service, Whiskeytown National Recreation Area, Whiskeytown, CA. Tim_Bradley@nps.gov

² Ecologist, National Park Service, Whiskeytown National Recreation Area, Whiskeytown, CA.

³ Biological Science Technician, National Park Service, Whiskeytown National Recreation Area, Whiskeytown, CA.

this biomass, but rather converts the standing brush to dead surface fuels, fire risk can still be high. Despite gaining acceptance as a landscape-scale treatment, significant uncertainty exists regarding the effects of these alterations on fire behavior in both prescribed fire and wildland fire scenarios.

Like many National Park Service units throughout the country, Whiskeytown National Recreation Area recently revised its Fire Management Plan (National Park Service 2003). This plan greatly expands the options available to park managers and includes a suite of mechanical treatments, such as manual thinning, small-scale logging, and vegetation mastication that have yet to be tested in the park or in similar habitat types elsewhere. With support funding from the Joint Fire Science Program, a research project was initiated in 2002 to provide managers with a better understanding of the effects of one of these treatments, vegetation mastication, on fire behavior and intensity.

Since fuel beds resulting from the mastication of shrubs and small trees are most similar to those of a logging slash fuel model, it is hypothesized that the increase in small-sized surface fuels would increase fire intensity and severity. The overall goal of this project was to evaluate key fire behavior indices and severity effects to vegetation in both masticated and unmanipulated vegetation during a spring prescribed burn. Specific objectives for the unmanipulated vegetation were consistent with prescribed burn treatments applied throughout the park, while separate project-specific objectives were developed for the application of fire to masticated vegetation (table 1). These objectives targeted the reduction in specific fuel classes and the retention of overstory trees.

Study Site

Whiskeytown National Recreation Area is located on the southeastern edge of the Klamath Mountains in Northern California. The climate is characterized as Mediterranean, with cool, wet winters and hot, dry summers. Temperature readings are often over 100°F (38 °C) from May through October and occasional sub-freezing temperatures occur from November through March. The annual precipitation averages 60 inches (152 cm) at

Table 1—Management objectives for the prescribed fire treatments in masticated and unmanipulated fuelbeds.

Objective	Targeted percent change	
	Masticated	Unmanipulated
Reduce surface fuel accumulation (litter, duff, 1, 10, 100, 1000 hr TLFM)	15 to 35	25 to 70
Reduce live density of small knobcone pine trees (<8 inch/20 cm d.b.h)	0 to 25	10 to 75
Reduce live density of all other small trees (<8 inch/20 cm d.b.h)	0 to 25	0 to 40
Limit mortality of overstory trees (>8 inch/20 cm d.b.h)	0 to 15	0 to 15
Reduce cover of live shrubs	0 to 25	15 to 75

park headquarters, most of which falls between November and April. The 45 acre study site is located in a low elevation (1,250 to 1,400 ft/380 to 460 m) area that has slopes less than 30 percent (the upper limit for the selected machinery). Overstory vegetation is dominated by black oak (*Quercus kelloggii*) and knobcone pine (*Pinus attenuata*), with limited presence of other species such as canyon live oak (*Quercus chrysolepis*), grey pine (*Pinus sabiniana*), and interior live oak (*Quercus wislizeni*). The understory vegetation is typically dense and dominated by whiteleaf manzanita (*Arctostaphylos viscida*), with toyon (*Heteromeles arbutifolia*) and poison oak (*Toxicodendron diversilobum*) also common.

Experimental Design and Treatments

The research site was stratified based on vegetation, slope, and aspect, resulting in the selection of ten different 1 to 2 acre (0.4 to 0.8 ha) treatment blocks. Each treatment block was divided into fourteen approximately equal-sized units, with two units from each block representing masticated (n=20) and unmanipulated (n=16) vegetation burned in the spring. The remaining experimental units are part of a separate long-term research project focusing on vegetation response to mastication and other fuels treatments.

Mastication treatments were completed in November of 2002 using an ASV Posi-Track™ with industrial brush-cutter. At least 90 percent of machine operations occurred over surfaces covered with chipped wood to limit soil disturbance and compaction (Poff 1996). To further minimize soil impacts, the tractor specifications required rubber tires or tracks, a vehicle no larger than 10,000 gross pounds (4,500 kg), an average of less than 3.5 pounds per square inch (0.25 kg/cm²) ground pressure, and operation on dry soil (Windell and Bradshaw 2000). The goal of this treatment was to reduce understory bulk density by 60 to 95 percent by thinning shrubs and small trees less than four meters in height. In areas where overstory trees were absent, a limited cover of shrub species was maintained.

Prescribed burn treatments were designed to be representative of treatments typically applied within the park. All fires were backing with respect to slope and/or wind, utilizing drip torches and applying a combination of strip and spot ignition patterns. Ambient weather conditions were recorded on-site by fire effects monitors. During the burning period (April-May 2003), temperature extremes ranged from 59°F to 71°F (15°C to 22°C), relative humidity ranged from 34 to 73 percent, and wind speeds averaged 2 mph (3 km/h) with a maximum wind speed of 6 mph (9.5 km/h). Soil moisture readings were very high (0.3 to 0.4 kPa tension) as recorded by a Delmhorst KS-D1 soil moisture meter at reference locations 18 inches (45 cm) below the surface.

Fire behavior and effects measures were recorded for each burn unit in four 1 m² fire behavior plots (n=140). Within each fire behavior plot, pre- and post-burn measurements were collected for litter, duff, 1-hr (<0.25 inches or 0.6 cm), 10-hr (0.25 to 1 inch or 0.6 to 2.5 cm), 100-hr (1 to 3 inches or 2.5 to 7.6 cm) and 1000-hr (>3 inches or 7.6 cm) time lag fuel moisture (TLFM) cover. In addition, percent cover values for herbaceous vegetation and bare ground were recorded. Using a method similar to Hobbs and Atkins (1988), a garden stake with pyrometers was located at the center of each fire behavior plot to record maximum temperature. Pyrometers were constructed using brass tags painted with heat-sensitive paint (OMEGALAQ®, Omega

Engineering, Inc.), and were positioned in three strata: 1) between the duff and soil layers; 2) on top of the litter; and 3) 0.5 m (1.64 ft) above the litter surface. During the burn, fire behavior data were recorded on the maximum and average flame lengths, flame zone depths, rates of spread, and fire types (head, backing, or flanking). One month after the burn, scorch estimates for dominant trees and shrubs were recorded for each burn unit and tree and shrub mortality estimates were recorded approximately six months post-burn.

To examine potential patterns in fire behavior, severity, and surface fuels, all fire behavior plots were characterized through a Principal Components Analysis (PCA) (Tabachnick and Fidell 1996). A two-tailed t-test (Zar 1996) was used to determine the difference in the mean PCA factor scores for masticated and unmanipulated vegetation. Similarly, a two-tailed t-test was used to determine the mean difference in flame length and flame zone depth for masticated and unmanipulated vegetation. To ascertain differences in pyrometer temperature between masticated and unmanipulated vegetation, a two-tailed t-test was used. A multiple regression (Zar 1996) was used to model relationships for aerial and litter level pyrometers with surface fuels and fine dead fuel moisture.

Results and Discussion

The effect of the brush mastication treatment did not result in a reduction of fuels, but rather the rearrangement of standing live material into dead and small-sized surface fuels. Prior to implementation of the mastication treatment, the fuels at the site were best characterized as a mix of fuel models 4, 8, and 9 (Anderson 1982). After mastication, the fuel bed changed drastically, with post treatment conditions representative of fuel model 11 (logging slash). This conversion of standing vegetation into downed woody debris resulted in an approximate 200 percent average cover increase in woody fuel loading for 1-hr and 1000-hr TLFM size classes, and greater than 300 percent average cover increase in 10-hr and 100-hr TLFM size classes. In addition to a surface fuel quantity increase, average shrub canopy cover was reduced from 64% down to 2% by the mastication treatment. This removal of canopy cover can contribute to an increase in air circulation, surface temperature, and direct solar radiation (Aussenac 2000), which can dry fuels quickly and increase flammability (Weatherspoon 1996). The results from this research strongly suggest that the combination of rearranging the structure of fuels while simultaneously altering the site microhabitat characteristics, led to an increased potential for high intensity fire.

To examine potential patterns between surface fuels and indices of fire behavior and severity, a Principal Components Analysis (PCA) was used (figure 1). Positively skewed data were transformed using the square root and the Pearson's product moment correlation coefficient (Zar 1996) was used to eliminate variables that were highly correlated (>0.6). The PCA illustrated differences between masticated and unmanipulated plots for Factor 1 scores. A two-tailed t-test on the PCA scores demonstrated a difference in the amount of surface fuels, fire behavior, and fire severity variables with mean Factor 1 scores for masticated plots (0.480) significantly ($P<0.001$) greater than those for unmanipulated vegetation (-0.583). The high Factor 1 scores for masticated plots indicate a high amount of surface fuels (litter, 1-hr, 10-hr, and 100-hr fuels), wide flame zone depth, and greater aerial temperatures. Plots in unmanipulated vegetation had a high percent cover

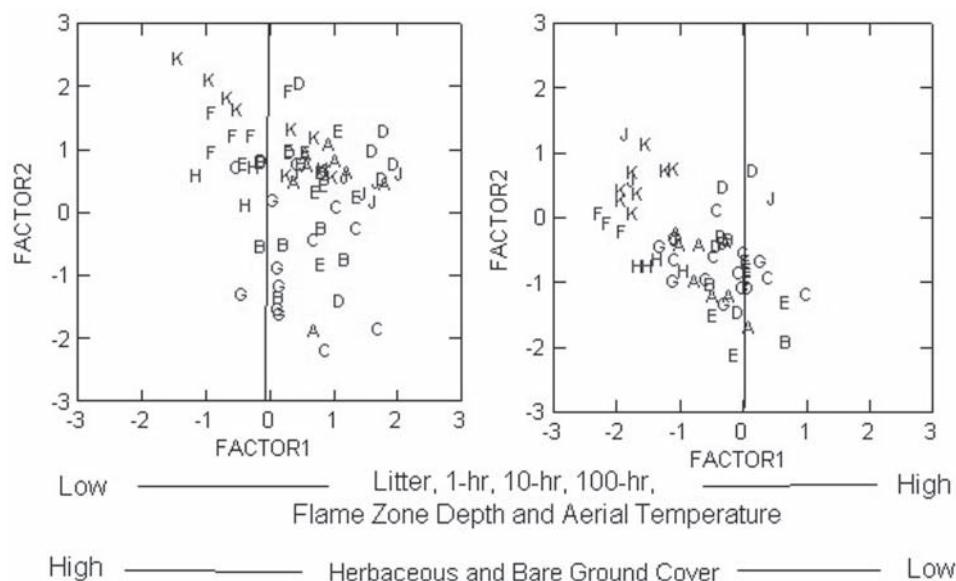


Figure 1—PCA scores for masticated (left) and unmanipulated (right) plots during the burn treatment.

of herbaceous species, bare ground, and low surface fuels, fire behavior and fire severity values.

A variety of fire intensity measures showed striking differences between the masticated plots and those in unmanipulated vegetation. A two-tailed t-test for both flame length and flame zone depth indicated greater values in masticated plots when compared to plots in unmanipulated vegetation. Mean flame length (29 inches/ 74 cm) and flame zone depth (19 inches/ 48 cm) were significantly greater ($P < 0.001$) in masticated plots than mean flame length (10 inches/ 25 cm) and flame zone depth (6 inches/ 15 cm) in the unmanipulated plots. Two of the three strata tested with pyrometers also indicated significant temperature differences between masticated and unmanipulated plots (figure 2). A two-tailed t-test showed that mean temperatures for litter (657°F/ 347°C) and aerial (277°F/ 136°C) pyrometers in the masticated plots were significantly greater ($P < 0.001$) than temperatures recorded for litter (219°F/ 104°C) and aerial (59°F/ 15°C) pyrometers in unmanipulated vegetation. While above ground temperatures were moderate to high, high duff and soil moistures moderated intensity effects to the soil, with only limited heating recorded by the lowest pyrometer. As a result of these conditions, duff reduction was not complete in either masticated (27 percent consumption) or unmanipulated (16 percent consumption) fuels.

The data for aerial and litter pyrometers were analyzed by multiple linear regression models to investigate the relationship among variables. With aerial pyrometer temperature as the dependent variable, the best fitting model ($P = 0.004$) included 100-hr fuels and fine dead fuel moisture as independent variables (table 2). With litter pyrometer temperature as the dependent variable, the best fitting model was also highly significant ($P = 0.026$) and included litter depth, 10-hr fuels, and 100-hr fuels as dependent variables (table 3). Despite their high significance, each of these models demonstrated relatively mediocre fit with $r^2 = 0.314$ for aerial pyrometers and $r^2 = 0.478$ for litter

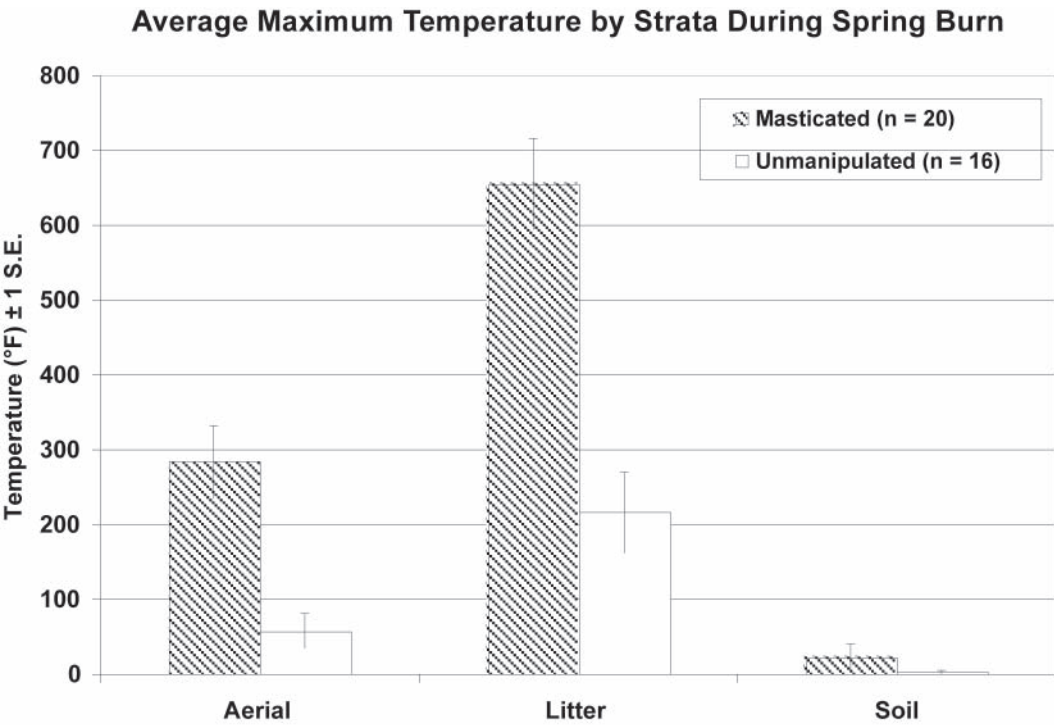


Figure 2—Average temperatures recorded by pyrometers during the burn treatment in masticated and unmanipulated plots. Aerial pyrometers were located 0.5 m/1.64 ft above the ground surface, litter pyrometers were located on the surface of the litter, and soil pyrometers were located between the duff and soil layers.

Table 2—Regression statistics for aerial (0.5 m/1.64 ft above ground surface) pyrometers

Model Term	Parameter estimate	SE	Pr(> t)
Intercept	357.9272	122.6933	0.0041
100 hr. Fuels ^a	14.4611	2.5365	0.0000
FDFM ^b	−28.1747	12.2782	0.0233

^a 100 hour TLFM size class
^b Fine dead fuel moisture

Table 3—Regression statistics for pyrometers placed at the litter surface.

Model Term	Parameter estimate	SE	Pr(> t)
Intercept	453.5598	201.7489	0.0262
Litter Depth	91.0512	21.3446	0.0000
10 hr Fuels ^a	8.6276	1.8347	0.0000
100 hr Fuels ^b	13.1951	4.0239	0.0013
FDFM ^c	−46.1797	19.2146	0.0176

^a 10 hour TLFM size class
^b 100 hour TLFM size class
^c Fine dead fuel moisture

pyrometers. It is probable that a more accurate quantification of the fuelbeds would have improved our results, although at a significant increase in time. Regardless, given the high level of variability that existed within individual fuelbeds, such findings are not surprising and perhaps highlight the differences frequently found between laboratory and field experiments. Of note is the correlation shown by fine dead fuel moisture in both models. While a coarse value, fine dead fuel moisture is sensitive to changes in canopy cover and regularly recorded ambient weather conditions.

Based on the multiple regression analyses, surface fuel loading was a primary driver of fire behavior, with significant fuel consumption differences noted between treatments (figure 3). With the exception of 1-hr fuels, total percent consumption in the masticated fuelbeds was higher for all TLFM size classes. It is probable that the apparently low consumption of 1-hr size class fuels in the masticated fuels (17 percent) was actually much higher, and includes larger 10-hr and 100-hr fuels that were only partially consumed during the burns. Interestingly, an increase was noted in 100-hr and 1000-hr TLFM size classes following the burn treatment in unmanipulated vegetation. While only a marginal increase, this finding is consistent with other monitoring completed at the park, reflecting the addition of recently killed vegetation to the surface fuelbed.

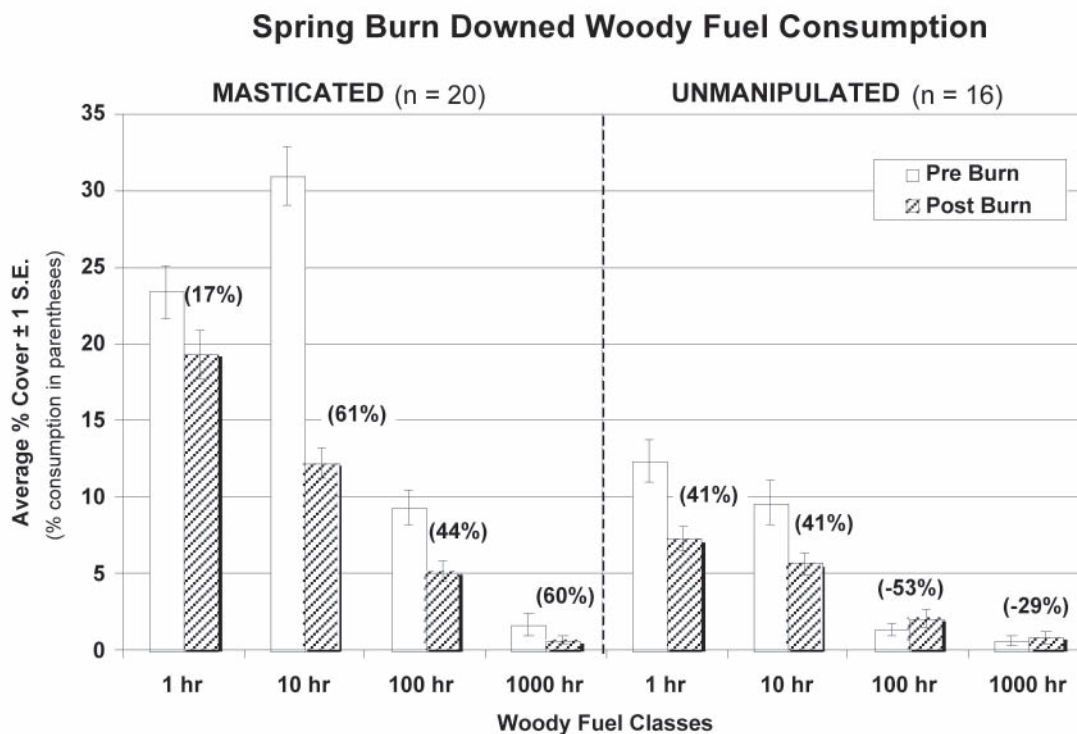


Figure 3—Consumption of downed woody fuels during the burn treatment in masticated and unmanipulated plots. Fuels are categorized as 1 hour, 10 hour, 100 hour, and 1000 hour time lag fuel moisture (TLFM).

The total surface fuel reduction objectives (table 1) were achieved in both masticated and unmanipulated vegetation, but the fire effects to live vegetation were more complex. In the unmanipulated units, reduction targets were met for pole-sized (<8 inches or 20 cm d.b.h.) trees and shrubs and there was no mortality of overstory (>8 inches or 20 cm d.b.h.) trees (table 4). However, in the masticated units, reduction and mortality targets were greatly exceeded for pole-sized trees, shrubs and overstory trees (table 4). Despite efforts by ignition crews to mitigate effects to overstory trees, the heat effects to these trees and to residual shrubs in the masticated units were severe. While applying prescribed fire during the early growing season was likely a contributing factor to this mortality, the increased fire intensity in masticated fuels was the primary cause.

Management Implications

Results from this study showed significant differences in fire behavior and effects during spring prescribed burns in units with masticated vegetation versus those with unmanipulated vegetation. These results strongly suggest that the differences were driven by the surface fuel conditions created as a direct result of the mastication treatment. Through time, decomposition and compaction of these materials may promote lowered fire intensity potential, but in the short term mastication appeared to contribute to an increase in fire severity and intensity.

While vegetation mastication followed by prescribed fire was a success from a fuel reduction standpoint, fire intensity in the masticated units was lethal for much of the residual vegetation. Since the mastication treatment had already eliminated shrubs and small trees, the effect of the prescribed burn on retained vegetation was undesirable. In natural areas the retention of overstory trees is a primary resource management concern during prescribed burns, and these results highlight the potential conflicts of burning in varied fuelbeds when objectives extend beyond surface fuel consumption.

While this study was restricted to one site, the results apply to many land management agencies that are interested in applying mastication treatments

Table 4—Average percent mortality of trees and shrubs during the spring burn treatment in masticated and unmanipulated plots.

	Overstory (>8 inch/20 cm d.b.h)		Pole (<8 inch/20 cm d.b.h.)	
	Unmanipulated	Masticated	Unmanipulated	Masticated
----- percent mortality ^a -----				
Knobcone Pine (<i>Pinus attenuata</i>)	0	16	15	66
Black Oak (<i>Quercus kelloggii</i>)	0	23	17	47
Canyon Live Oak (<i>Quercus chrysolepis</i>)	0	49	21	98
Shrubs	Unmanipulated		Masticated	
	30		96	

^aMortality figures for resprouting oak species refers to top-killed individuals.

for reduction of understory vegetation. The following list highlights some of the management implications derived from this research:

- 1) Mastication of vegetation results in a short to medium-term increase in fire intensity and severity potential. Where utilized, mastication prescriptions should consider the need for greater canopy retention to increase shading at the soil surface, thus increasing fine dead fuel moisture and contributing to slower seasonal drying of fuels. In addition, lowering intensity of mastication will directly reduce total surface fuel load.
- 2) Mortality of remaining overstory vegetation may be high in areas where masticated treatments are followed by prescribed burning. Managers may be able to reduce this secondary mortality by:
 - Decreasing the level of mastication intensity. This will contribute to lower fire behavior indices and severity results by reducing surface fuel loading, increasing shading of fuels, decreasing wind circulation and thus, drying of surface fuels.
 - Applying fire during mild conditions. Mastication treatments significantly alter the fuelbed and result in significantly different fire behavior than in unmanipulated vegetation. Prescriptions must consider these differences in expected behavior and subsequent severity.
 - Avoiding spring or early growing-season burns when desirable species are in a susceptible period of development. The post green-up application of fire in this study coincided with a vulnerable phenologic period in plant development, when leaf, bud, and cambium tissues were particularly susceptible to thermal effects. Prescription windows that are scheduled during the dormant season would likely minimize severity effects to retained vegetation.
- 3) Short-term increases in fire intensity occur following mastication; however, long-term trends are still unknown. This study was conducted six months after mastication when the masticated fuelbed was still loosely arranged on the surface. Through time, it is expected that decomposition and compaction of the masticated fuels would occur, lowering the potential fire intensity, but the rate of change is not known. Research on assessing changes in masticated vegetation over time would provide valuable information for long-term management.

Acknowledgments

The authors would like to thank Whiskeytown NRA Fire and Resource Management personnel for assistance in all aspects of this project. In particular, we want to thank Jake Blaufuss for setting up the initial treatment polygons, and Justin Cully, Johanna D'Arcy, Ed Waldron, James Savage, Chris Sprague, Brian Rasmussen and Joe Svinarich for fire behavior data collection assistance. We also want to thank North Tree Fire International for assistance with the mastication treatment, and the California Conservation Corps, California Department of Forestry and Fire Protection, and USFS, Redding Hotshots and Redding Smokejumpers for assistance with the burn treatments. This project was made possible by funds provided by the Joint Fire Science Program.

References

- Anderson, Hal E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, Utah : U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experimental Station. 22 p.
- Aussenac, G. 2000. Interactions between forest stands and microclimate: Ecophysiological aspects and consequences for silviculture. *Ann. For. Sci.* 57: 287-301.
- Deeming, John E.; Burgan, Robert E.; Cohen, Jack D. 1977. The National Fire-Danger Rating System—1978. Gen. Tech. Rep. INT-39. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 63 p.
- Hobbs, R. J.; Atkins, Lyn. 1988. Spatial variability of experimental fires in south-west Western Australia. *Australian Journal of Ecology*. 13(3): 295-299.
- National Park Service. 2003. Fire management plan: environmental impact statement. Whiskeytown, CA: National Park Service, Whiskeytown National Recreation Area. 269 p.
- Poff, R.J. 1996. Effects of silvicultural practices and wildfire on productivity of forest soils. In: *Sierra Nevada Ecosystem Project: Final report to Congress*, vol. II, chap. 16. Davis: University of California, Centers for Water and Wildland Resources.
- Tabachnick, B. G.; Fidell, L. S. 1996. *Using Multivariate Statistics*, 3rd ed. New York, NY: HarperCollins Publishers Inc. 880 p.
- Tyler, C. M.; D'Antonio, C. M.. 1995. The effects of neighbors on the growth and survival of shrub seedlings following fire. *Oecologia (Berlin)* 102(2): 255-264.
- Weatherspoon, C. P. 1996. Landscape-level strategies for forest fuel management. In *Sierra Nevada Ecosystem Project: Final report to Congress*, vol. II, chap. 56. Davis: University of California, Centers for Water and Wildland Resources.
- Windell, Keith; Bradshaw, Sunni. 2000. Understory biomass reduction methods and equipment. Tech. Rep. 0051-2828-MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development. Center. 32 p.
- Zar, J. H. 1996. *Biostatistical Analysis*, 3rd ed. Upper Saddle River, NJ: Prentice-Hall, Inc. 662 p.

Assessing Mitigation of Wildfire Severity by Fuel Treatments — An Example From the Coastal Plain of Mississippi

Erik J. Martinson¹ and Philip N. Omi²

Abstract—Fuel treatments such as prescribed fire are a controversial tenet of wildfire management. Despite a well-established theoretical basis for their use, scant empirical evidence currently exists on fuel treatment effectiveness for mitigating the behavior and effects of extreme wildfire events. We report the results of a fire severity evaluation of an escaped prescribed fire that burned into an area previously treated with repeated prescribed fires. We observed significantly lower scorch heights, crown damage, and ground char in the treated area. We attribute the moderated fire severity in the treated area to a significantly altered fuel profile created by the repeated prescribed fires. Though our results represent just one treatment area in a single wildfire, they add to a depauperate database and bring us a step closer to defining the conditions under which fuel treatments are an effective pre-suppression strategy.

Introduction

Fuel treatment effectiveness as a pre-suppression strategy is a controversial tenet of wildfire management with a strong theoretical foundation, but scant empirical evaluation. Several recent reviews provide a survey of the extant literature on the scientific justification for fuel treatment programs (Graham and others 2004; Carey and Schumann 2003; Fernandes and Botelho 2003). A perusal of the publications cited in these reviews and those published subsequently (prior to March 2006) reveals that much of the evidence of fuel treatment effectiveness comes from the results of simulations based on models of fire spread (Rothermel 1972) and crown fire potential (Rothermel, 1991). More than half (26 of 49) of the analytical studies conducted in North America rely on simulations and, of these, half (13) employ hypothetical treatments as well as hypothetical wildfires. Many questions related to fuel treatments can only be addressed in a modeling environment, such as optimal landscape placement (Finney 2001) or potential effectiveness under varying climate regimes. However, the ability of current fire behavior models to reflect reality has received little validation, particularly under the extreme conditions that produce large wildfire events (Cruz and others 2005). Thus, the results of modeling experiments are best viewed as hypotheses awaiting an empirical test.

Nonetheless, simulation experiments have been necessary to establish a scientific basis for the effectiveness of fuel treatments, given the obvious limitations on experimentation with actual wildfires. Just one study exists that tested the effectiveness of a fuel treatment under experimental conditions extreme enough to produce crown fire activity (Alexander and Lanoville 2004). This study was conducted in the boreal forest of the Canadian Northwest Territories and the authors conclude that thinning without treatment

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

¹ Research Associate, Department of Forest Rangeland and Watershed Stewardship, Colorado State University, Fort Collins, CO.
erikm@warnercnr.colostate.edu

² Professor Emeritus, Department of Forest Rangeland and Watershed Stewardship, Colorado State University, Fort Collins, CO.

of surface fuels is largely ineffective, though the sample size was very limited and no statistical analysis has been reported.

The remainder of the evidence of fuel treatment effectiveness in North American ecosystems relies on natural experiments in which an actual wildfire serendipitously encountered one or more fuel treatment areas. Though there have been recent efforts to collect fire behavior data *in situ* as wildfires encounter fuel treatments (Fites-Kauffman 2001), all 22 of the natural experiments published to date have relied on *post facto* analysis. However, just 11 of these studies included a statistical analysis of the treatment effect and only seven attempted to control for the influences of topography and weather, which along with fuels are the determinants of fire behavior. Rather incredibly, only four studies have been published that included both a statistical test and adequate control to discern a fuel treatment effect in an actual wildfire.

Pollet and Omi (2002) evaluated the severity of four wildfires that burned over treated areas in ponderosa pine forests in Oregon, Washington, California, and Arizona. One of the fires encountered a prescribed burn, while the other three encountered thinning treatments where the activity fuels were effectively removed, either by burning or whole-tree removal. The treatments were completed 1 to 11 years prior to wildfire and in all cases fire severity was found to be significantly lower in treated stands.

Raymond and Peterson (2005) evaluated the severity of a wildfire in mixed conifer forest of coastal Oregon that burned over four thinning treatments, one of which included subsequent underburning. All thinning was completed 6 years prior to the wildfire and the underburn was done 5 years later. Fire severity was found to be significantly greater in two of the three thinned areas that were not underburned, while the third showed no effect. However, the wildfire burned around the underburned treatment without entering.

Cram and others (2006) evaluated the severity of three wildfires that burned over treatments in ponderosa pine forests in Arizona and New Mexico. All of the wildfires included areas that were thinned followed by prescribed burns and one of them also included areas where the slash was scattered but left on-site. All treatments reduced wildfire severity, but the treatments that were not prescribe-burned were less effective.

Skinner and others (*in press*) evaluated the severity of a wildfire in ponderosa pine dominated forest in northern California that burned over five thinning treatments, all but one of which were subsequently treated with prescribed fire. Fire severity was found to be significantly lower in the thinned units where the slash was treated, but no effect was observed in the thin-only treatment.

This paper describes how the fuel treatment assessment methods followed by Pollet and Omi (2002) were applied again to provide much needed additional empirical information from a wildfire that burned into an area that had been previously treated with repeated prescribed burns in coastal Mississippi. We follow with a discussion of how our methods have since evolved to overcome certain limitations presented by this site.

Methods

Study Area

The study site is located on and adjacent to the Fontainebleau Unit of the Mississippi Sandhill Crane National Wildlife Refuge. The Refuge is approximately 8 km east of Ocean Springs in Jackson County, Mississippi in

the Gulf Coastal Plain physiographic province. Topography is flat throughout at an elevation of 6m. Slash pine (*Pinus elliottii* Englem.) is dominant in the forest canopy with longleaf pine (*Pinus palustris* Mill.) also present. Sub-canopy species include persimmon (*Diospyros virginiana* L.) and black gum (*Nyssa sylvatica* Marsh). Vines (e.g., *Vitis* spp. and *Smilax* spp.), bays (*Persea* spp.), and gallberry (*Ilex coriacea* (Pursh) Chapm.) are abundant in the understory.

The US Fish and Wildlife Service established the Refuge in 1975 to protect the endangered Mississippi Sandhill Crane (*Grus canadensis pulla* Aldrich) and its wet pine savannah habitat. Management of the Refuge includes extensive use of prescribed fire to reduce hazardous fuels and restore the open structure of longleaf pine savannahs (Platt and others 1988). One such prescribed fire became the Fontainebleau wildfire at 1430 hours on April 18, 1999 when it spotted across a railroad and onto private property containing untreated fuels best characterized by Fuel Model 7 (Anderson 1982). The wildfire exhibited extreme behavior and at 1600 hours spotted back across the railroad and into a stand that Refuge managers had burned in 1988, 1992, and 1998 with the objective of converting fuels to approximate Model 2 conditions. The Fontainebleau fire grew to a final size of 142 ha including 36.5 ha on Refuge lands last treated in 1998. Hourly weather conditions from an on-site Remote Automated Weather Station are provided in Table 1.

Data Collection

We collected data in September 1999 to quantify fuels and fire severity differences between treated and untreated stands affected by the Fontainebleau Fire. Data were collected in nine variable radius plots in each of the two stand types (treated and untreated). Plot areas were defined with a Cruiser's Crutch with a metric basal area factor of 2 (Avery and Burkhart 1994). We employed a systematic sampling design in which plot centers were separated by 60 m along three transects also separated by 60 m. A 60 m buffer on either side of the railroad that separates the treated and untreated areas minimized edge effects. Figure 1 depicts a map of the fire perimeter, treatment area, and plot locations.

The trees sampled at each plot were distinguished by species and crown position and measured for the following aerial fuel descriptors: stand density, tree size and height, and height to the base of the pre-fire live crown. The

Table 1—Weather conditions during the Fontainebleau Fire on April 18, 1999 (weather data from an onsite Remote Automated Weather Station).

	Wind	Wind		Relative	Dead Fuel Moisture Content		
Time	speed	Direction	Temperature	Humidity	1hr ^a	10hr ^b	100hr ^c
<i>hr</i>	<i>km per hr</i>	<i>Azimuth</i>	<i>°C</i>	<i>-----percent-----</i>			
1400	10.9	315	21.0	27	5.5	6.7	15
1500	9.0	270	22.3	28	5.5	6.7	15
1600	12.1	315	21.3	28	5.6	6.6	15
1700	9.7	315	21.3	29	5.9	5.8	15

^a Dead fuel moisture content is expressed by standard equilibrium time lag classes: 1hr refers to fuels less than 0.25 inch diameter

^b 10hr fuels are less than 1 inch in diameter

^c 100hr fuels are less than 3 inches in diameter

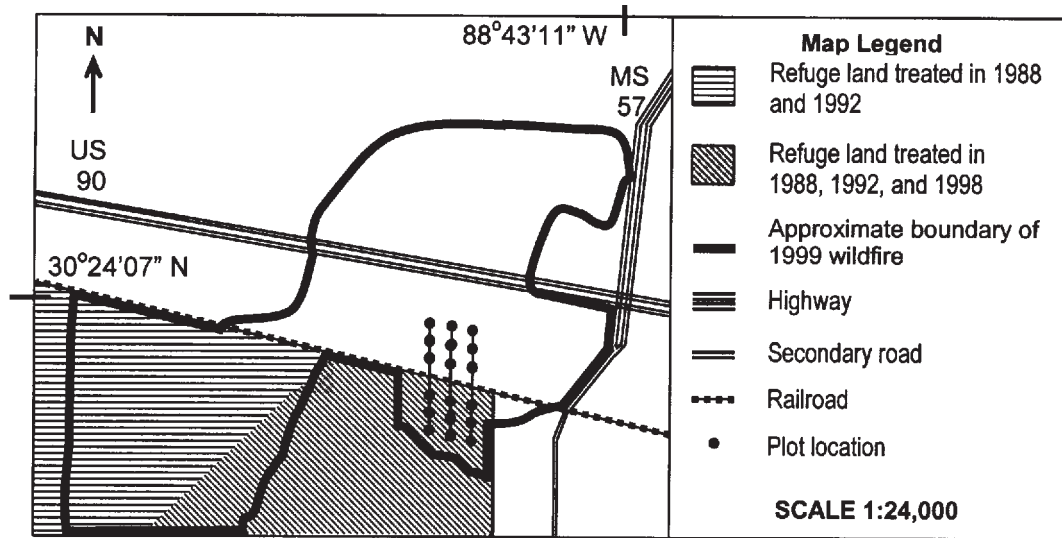


Figure 1—Plot locations in relation to fuel treatments involved in the 1999 Fontainebleau wildfire on and adjacent to the Mississippi Sandhill Crane National Wildlife Refuge. The fire started as a prescribed burn on the Refuge (in the area shaded with horizontal lines), but was declared a wildfire when it spotted across the railroad and onto private property. The wildfire later spotted back across the railroad and into an area the Refuge had previously treated.

base of the pre-fire live crown was judged to be the lowest branch with twigs, though this may have been an overestimate in severely burned plots if lower live branches or twigs were completely consumed; or an underestimate if lower branches with twigs were needleless prior to the fire. We also attempted to quantify the pre-fire density and height of shrub fuels (an important component of Fuel Model 7) by sampling four 1 m² circular plots located at 90 degree angles and 17.85 m from each plot center. No attempt was made to quantify pre-fire conditions of other surface fuel components post hoc, since the fine fuels that contribute most to surface fire spread are consumed in most fires (Ottmar and others 1993).

Following the methods used by Pollet and Omi (2002), we evaluated wildfire severity at each plot in terms of stand damage, as well as upward and downward heat pulse components. Stand damage ratings were adapted from Omi and Kalabokidis (1991) while the downward heat pulse was estimated with ground char ratings adapted from Ryan and Noste (1985). Rating criteria are provided in table 2. Stand damage was evaluated for the plot as a whole, while the downward heat pulse was estimated with ground char ratings in four 30 m x 60 m subplots at the same locations as the shrub subplots described above.

Table 2—Criteria used to evaluate fire severity in sampled stands.

Rating	Stand Damage Criteria	Ground Char Criteria
0	All tree crowns unscorched.	No evidence of surface fire.
1	Partial scorch on at least 1 tree, but some trees unscorched.	Litter and twigs charred.
2	Partial scorch on all tree crowns, but few trees completely scorched.	All twigs, leaves, and standing grasses consumed, branches and logs charred.
3	Nearly all tree crowns completely scorched, but few crowns consumed.	Branches and logs mostly consumed.
4	Nearly all tree crowns consumed.	

The height of needle scorch on the coniferous trees sampled at each plot was measured as an indicator of fireline intensity (Van Wagner 1973). Percent canopy scorch was ocularly estimated on all trees, as well. Since height of needle scorch underestimates fireline intensity on trees that are either unscorched or completely scorched (the upper bound of scorch height is limited by tree height, while the lower bound is limited by crown base height), we modified calculations for average scorch height at each plot by excluding measurements from trees that were uninformative or misleading. Specifically, only the following measurements contributed to plot averages for scorch height:

- 1) Scorch heights of all partially scorched trees.
- 2) Tree heights of completely scorched trees added sequentially by decreasing height until average scorch height was maximized.
- 3) Bole char heights of unscorched trees added sequentially by decreasing height until average scorch height was maximized.
- 4) Crown base heights of unscorched trees added sequentially by increasing height until average scorch height was minimized.

Data Analysis

Standard statistical software (SAS Institute 2001) was used to conduct two-sample one-tail parametric tests for comparisons of continuous variables between treated ($n = 9$) and untreated ($n = 9$) sample plots. Specifically, we tested the following null hypotheses:

H_{01} : Vertical and horizontal fuel profiles do not differ between the area treated with prescribed fires and the untreated area.

H_{01a} : Trees are not larger (in diameter and height) in the treated area.

H_{01a} : Crown bases are not higher in the treated area.

H_{01a} : Shrubs are not shorter in the treated area.

H_{01b} : Densities of trees and shrubs are not greater in the untreated area.

H_{02} : Wildfire severity does not differ between the area treated with prescribed fires and the untreated area.

H_{02a} : Scorch height is not greater in the untreated area.

H_{02b} : Crown volume scorch on overstory trees is not greater in the untreated area.

H_{02c} : Stand damage is not greater in the untreated area.

H_{02c} : Ground char depth is not greater in the untreated area.

Non-parametric Wilcoxon tests were used for ordinal categorical data (that is the fire severity ratings). Significance levels for all tests were adjusted by partial Bonferonni correction to account for multiple comparisons (the Bonferonni adjustment was increasingly liberalized as the correlations among the set of compared variables increased (see *ad hoc* adjustments to the Bonferonni procedure in Sankoh and others (1997) or Uitenbroek (2001))).

Results

The forest treated with repeated prescribed fires on the Mississippi Sandhill Crane National Wildlife Refuge was found to have significantly different fuel profiles than the adjacent unmanaged private forest (table 3). The untreated plots had nearly seven times as many trees as the treated plots and these

Table 3—Comparison of stand conditions and fire severity indicators between treated and untreated stands within the Fountainebleau fire (means with standard deviations in parentheses).

Variable	Treated (n = 9)	Untreated (n = 9)
Tree diameter (cm)	20.9 ^e (3.4)	10.7 (4.7)
Tree height (m)	16.5 ^c (2.5)	10.6 (4.2)
Height to crown (m)	11.1 ^c (2.2)	7.3 (2.7)
Tree density (# per ha)	373 ^b (224)	2,496 (2,092)
Tree basal area (m ² per ha)	14.2 (7.8)	19.1 (10.8)
Shrub height (cm)	61.2 ^c 17.2	164.3 (77.9)
Shrub density (# per m ²)	15.9 (5.8)	13.7 (3.7)
Scorch height (m)	10.0 ^b (2.9)	15.4 (5.0)
Crown volume scorch (percent)	14 ^e (22)	99 (1)
Stand damage rating	0.8 ^e (0.7)	3.1 (0.8)
Ground char rating	1.0 ^b (0.0)	1.2 (0.2)

Treatment means followed by a superscript indicate a significant difference from the untreated mean in the hypothesized direction as follows:

^a p<0.1.

^b p<0.05.

^c p<0.01.

^d p<0.001.

^e p<0.0001.

were substantially smaller in diameter and height. Trees in the treated plots had twice the girth and were 50 percent taller than those in the untreated plots. Live crown bases were nearly twice as high off the ground in treated plots compared to untreated plots where shrubs were more than twice as tall. However, no significant difference was found in shrub density between the two sampled areas.

The two areas with distinctly different fuel profiles were observed to have experienced distinctly different wildfire severity (fig. 2, table 3). Average height of needle scorch was nearly twice as high in the untreated plots. With very few exceptions crown volume scorch in the untreated plots was 100 percent and significantly greater than in the treated plots. Ground char was light in all the treated plots, but somewhat deeper in the untreated plots.



Figure 2—Adjacent treated (a) and untreated (b) stands burned by the Fontainebleau fire.

Discussion

The differences we observed between the treated and untreated areas burned over by the Fontainebleau fire were dramatic. Still, our highly significant results may be conservative, since the 1998 prescribed fire that served as our treatment was reportedly more intense than the subsequent wildfire when it burned in the treatment area. Thus, the scorch heights and crown damage that we observed in the treated area probably resulted from the treatment itself, masking the less severe effects that resulted from the wildfire.

Vertical and horizontal fuel continuity was clearly greater in the private unmanaged forest, as evidenced by taller shrubs, lower tree crowns, and higher tree density. We attribute the lower severity observed on the Refuge primarily to a less hazardous fuel profile that resulted from distinct land management practices, most notably the repeated application of prescribed fire.

However, several caveats associated with this study bear mention. Unlike completely randomized pre-planned experiments, retrospective studies such as this one are inherently prone to selection bias both in the choice of study sites and the location of sample plots. Further, the availability of treatment replicates that might be considered independent samples is beyond the control of the investigators.

When the Fontainebleau fire was selected for investigation, our approach to identifying potential study sites relied on advertising our interest and criteria on relevant electronic list serves and at professional meetings attended by land managers. It soon occurred to us, however, that we might only be contacted in the case of an obviously effective treatment. We have since taken a more rigorous approach to defining the universe of possible study sites in any given year and now contact land managers directly wherever a wildfire exceeds 4,000 ha (10,000 acres).

Wildfires smaller than 4,000 ha are unlikely to encounter a single fuel treatment area, much less multiple treatments. Prior to the recent expansion of fuel treatment initiatives it was rare even for large wildfires to encounter more than one treatment. Unfortunately, any analysis of the effect of a single treatment must be based on pseudo-replicated samples (Hurlbert 1984), resulting in underestimated variance and compromised statistical tests. Such was the case with Fontainebleau, as well as all of Pollet and Omi's (2002) study sites. Few fuel treatment studies have been published based on samples from (approximately) replicated treatments and all but Cram and others (2006) relied on an analysis of remote sensing data that failed to control for the effects of weather and topography (for example, Weatherspoon and Skinner 1995; Martinson and others 2003, Finney and others 2005). However, since sampling Fontainebleau we have been able to restrict our investigations to wildfires that burned over at least three spatially dispersed areas that were similarly treated. We have now completed data collection from eight such study areas.

Once a wildfire is selected for investigation, we follow the procedures established by Pollet and Omi (2002) to minimize potential bias in locating sample plots. Plot locations are selected prior to any field visits and based solely on maps of treatment boundaries, roads, streams, vegetation, topography, and wildfire progression. Comparison plots are situated such that they straddle a treatment boundary, burned on the same day and under similar weather conditions, and have similar slope, aspect, elevation and tree species. We further seek to avoid areas that were a focus of fire control activities, as well as treatment boundaries defined by a significant fuel break, such as a major

road or stream. The straddle point along each treatment boundary is then chosen by random number generation, if any choice remains after all criteria are satisfied. The Fontainebleau site met all these criteria with the notable exception of a railroad separating the treated and untreated areas. While this was a substantial fuel break, it failed to stop fire spread; not once but twice. Further, the fire was not even curtailed by a much wider divided highway that included a mown median. We therefore concluded that any reduction in fire severity accomplished by the prescribed burns was undiminished by the presence of the railroad.

A final caveat for the Fontainebleau site is the unknown management history of the privately owned stand that served as our untreated control. While no activity has occurred in this stand since establishment of the Wildlife Refuge in 1975, its condition differed from the treated stand to such a degree that we find it difficult to believe three prescribed fires alone accomplished the difference. Rather, the untreated stand had probably been clearcut sometime in the past with no subsequent management (personal communication from Tony Wilder, Refuge Fire Management Officer). Nonetheless, the Fontainebleau site illustrates the differential consequences of fuels management and lack thereof when a wildfire occurs.

Conclusion

Like all studies of fuel treatment effectiveness, the data from the Fontainebleau fire are limited in many respects. Nonetheless, the results of this study provide a rare addition to a depauperate literature. Fuel treatment activities are expanding rapidly on public lands despite minimal empirical evidence to support their use. At least one beneficial consequence of this should be an increase in the number of wildfires that burn over multiple treatments, providing greater opportunity to achieve a semblance of replication and control in future retrospective studies of fuel treatment effectiveness. Thus fuel treatment activities are perhaps best viewed as experiments that provide potential learning opportunities. Knowledge must be gleaned from both the successes and the failures so that we might eventually define the conditions under which fuel treatments are an effective pre-suppression strategy for the mitigation of extreme wildfire behavior and effects. Every effort to collect empirical information from natural experiments such as that presented by the Fontainebleau fire brings us a step closer to this end.

Acknowledgments

We thank Malia Boyum for field assistance and Tony Wilder for facilitating our field visit and providing fire weather and behavior information. The Joint Fire Science Program funded this research.

Literature Cited

Alexander, M. E.; Lanoville, R. A. 2004. The international crown fire modeling experiment fuel treatment trials. Tall Timbers Fire Ecology Conference Proceedings 22: 222.

- Anderson, H. E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-GTR-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 19 p.
- Avery, T. E.; Burkhardt, H. E. 1994. Forest measurements, 4th edition. New York, NY: McGraw-Hill Book Co. 408 p.
- Carey, H.; Schumann, M. 2003. Modifying wildfire behavior – the effectiveness of fuel treatments. Santa Fe, NM: National Community Forestry Center Southwest Region Working Paper #2. 26 p.
- Cram, D. S.; Baker, T. T.; Boren, J. C. 2006. Wildland fire effects in silviculturally treated vs. untreated stands of New Mexico and Arizona. Research Paper RMRS-RP-55. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 28 p.
- Cruz, M. G.; Alexander, M. E.; Wakimoto, R. H. 2005. Development and testing of models for predicting crown fire rate of spread in conifer forest stands. Canadian Journal of Forest Research 35: 1626-1639.
- Fernandes, P. M.; Botelho, H. S. 2003. A review of prescribed burning effectiveness in fire hazard reduction. International Journal of Wildland Fire 12: 117-128.
- Finney, M. A. 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. Forest Science 47: 219-228.
- Finney, M. A.; McHugh, C. W.; Grenfell, I. C. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. Canadian Journal of Forest Research 35: 1714-1722.
- Fites-Kauffman, J. 2001. Real-time evaluation of effects of fuel-treatments and other previous land management activities on fire behavior during wildfires. Research proposal funded by the United States Departments of Agriculture and Interior Joint Fire Science Program.
- Graham, R. T.; McCaffrey, S.; Jain, T. B. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. Gen. Tech. Rep. RMRS-GTR-120. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 43 p.
- Martinson, E. J.; P. N. Omi; W. D. Sheppard. 2003. Fire behavior, fuel treatments, and fire suppression on the Hayman fire. Part 3. Effects of fuel treatments on fire severity. Gen. Tech. Rep. RMRS-114: 96-122. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
- Omi, P. N.; Kalabokidis, K. D. 1991. Fire damage on extensively versus intensively managed forest stands within the North Fork Fire, 1988. Northwest Science 65: 149-157.
- Ottmar, R. D.; Burns, M. F.; Hall, J. N.; Hanson, A. D. 1993. CONSUME user's guide. Gen. Tech. Rep. PNW-GTR-304. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 118 p.
- Platt, W. J.; Evans, G. W.; Rathburn, S. L. 1988. The population dynamics of a long-lived conifer (*Pinus palustris*). The American Naturalist 131: 491-525.
- Pollet, J.; Omi, P. N. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. International Journal of Wildland Fire 11: 1-10.
- Raymond, C. L.; Peterson, D. L. 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. Canadian Journal of Forest Research 35: 2981-2995.
- Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. Research Paper INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 40 p.
- Rothermel, R. C. 1991. Predicting behavior and size of crown fires in the northern Rocky Mountains. Research Paper INT-RP-438. U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 46 p.

- Ryan, K. C.; Noste, N. V. 1985. Evaluating prescribed fires. Gen. Tech. Rep. INT-GTR-182: 230-238. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.
- Sankoh, A. J.; Huque, M. F.; Dubey, S. D. 1997. Some comments on frequently used multiple endpoint adjustment methods in clinical trials. *Statistics in Medicine* 16: 2529-2542.
- SAS Institute, Inc. 2001. The SAS system for windows, release 8.2. Cary, NC: The SAS Institute, Inc.
- Skinner, C. N.; Ritchie, M. W.; Hamilton, T.; Symons, J. In press. Effects of prescribed fire and thinning on wildfire severity: the Cone fire, Blacks Mountain Experimental Forest. In: *Proceedings of the 25th Vegetation Management Conference*, Redding, CA.
- Uitenbroek, DG. 2001. Simple interactive statistical analysis: Bonferonni correction. URL: <http://home.clara.net/sisa/bonhlp.htm#Corr>.
- Van Wagner, C. E. 1973. Height of crown scorch in forest fires. *Canadian Journal of Forest Research* 3: 373-378.
- Weatherspoon, C. P.; Skinner, C. N. 1995. An assessment of factors associated with damage to tree crowns from the 1987 wildfires in northern California. *Forest Science* 41: 430-451.

A Fuel Treatment Reduces Potential Fire Severity and Increases Suppression Efficiency in a Sierran Mixed Conifer Forest

Jason J. Moghaddas¹

Abstract—Fuel treatments are being widely implemented on public and private lands across the western U.S. While scientists and managers have an understanding of how fuel treatments can modify potential fire behavior under modeled conditions, there is limited information on how treatments perform under real wildfire conditions in Sierran mixed conifer forests. The Bell Fire started on 9/22/2005 on the Plumas National Forest, CA. This fire burned upslope into a 1-year old, 390-acre mechanical fuel treatment on private land. Prior to impacting the fuel treatment, the main fire ignited spot fires 400 feet into the treated area. Within the treated area, loadings of 1, 10, and 100-hour fuels averaged 5.2 tons per acre. Stand density averaged 73 trees per acre, with a live crown base of 30 feet, and 36% canopy cover. This fuel treatment resulted in: 1) increased penetration of retardant to surface fuels, 2) improved visual contact between fire crews and the IC, 3) safe access to the main fire, and 4) quick suppression of spot fires. This treatment was relatively small and isolated from other fuel treatments but resulted decreased severity, suppression costs, and post fire rehabilitation needs leading to cost savings for local public and private land managers.

Introduction

Fuel treatments are being widely implemented on public and private lands across the western United States (Stephens 2005). Over 11 million acres of hazardous fuel reduction and landscape restoration activities have been implemented since federal fiscal year 2000 (Healthy Forests Report 2005). The stated goals of these treatments are to: “1) Directly reduce wildfire threats to homes and communities that are adjacent to or within the wildland urban interface (WUI), 2) Treat areas outside of the wildland-urban interface (non-WUI) that are at greatest risk of catastrophic wildland fire. These high priority non-WUI treatments move towards restoring fire to its historical role and 3) Maintain previous treatments to ensure resiliency to catastrophic wildland fire and implement activities that are in line with other long-term management goals” (Healthy Forests Report 2005).

While scientists and managers have an understanding of how fuel treatments can modify potential fire behavior under modeled conditions (Stephens and Moghaddas 2005), there is limited information on how treatments perform under real wildfire conditions in Sierran mixed conifer forests (Fites and Henson 2004). Public land managers are often tasked with designing projects to meet “desired future conditions” for fuel treatments, though there is limited information on what these conditions should be across a broad range of site classes and forest types. While several fires have been documented by fire managers burning or spotting into recently established fuel treatments

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

¹ Fire Ecologist, Plumas National Forest, Quincy, CA. jmoghaddas@fs.fed.us

(Beckman 2001; Hood 1999), relatively few of these events are formally studied to determine the effects of the fuel treatment on fire behavior and severity in Sierran mixed conifer forests.

The purpose of this paper is to document one example of how a fuel treatment influenced fire behavior and enhanced suppression efficiency in a mixed conifer stand within the wildland urban interface. Secondly, this paper quantifies a stand structure which was functioned as an effective fuel treatment under the weather conditions described.

Methods

Study Site

The study area is on the Beckworth Ranger District of the Plumas National Forest, approximately 1 mile south of Highway 89 at Lee Summit. The treatment described was established on private timberlands owned by the Soper-Wheeler Company. The treatment unit is located within the 1.5 mile extended wildland urban interface of Spring Garden, a Community at Risk (Callenberger and Lunder 2006; PCFSC 2005). The parcel is bordered on two sides by untreated National Forest Land (Figure 1, Figure 2). The fuel treatment was established on the north side of a ridge, immediately above the Middle Fork of the Feather River Drainage. The dominant aspect of the treated area is north facing with an average slope of 11 percent. The area within the treatment is classified as a site class II (Dunning 1942). Data available from the timber harvest plan and associated inventory plots were used to establish pre-treatment stand conditions. Post treatment, three 1/10th acre fixed radius plot were established along a transect which ran through the area impacted by spot fires. These plots were measured within 2 months of the fire.

Treatment Prescription

The forest type is Sierran Mixed Conifer forest dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), incense cedar (*Calocedrus decurrens* [Torr.] Floren.), ponderosa pine (*Pinus ponderosa* Dough. Ex. Laws), sugar pine (*Pinus lambertiana* Dougl.), white fir (*Abies concolor* Gord. & Glend.), and California black oak (*Quercus kelloggii* Newb.) (table 3). Prior to treatment, stand basal area was 258 ft² per acre and tree density was 478 trees per acre. Stands were thinned in the summer of 2005 under a selection harvest (CDF 2003) using a leave tree mark. Biomass and sawlog material was removed mechanically using a whole tree harvest system. Sub-merchantable material and tops were chipped at the landing and hauled to a local mill. An average of 2,460 board feet and 8.6 bone dry tons of biomass per acre were removed from the project area (Violett 2005).

General Fire Information

The Bell fire was reported at 12:13 on September 22nd 2005 (Table 1). The fire was accidentally ignited by railroad activity along the tracks immediately downhill and below the project area (Figure 1). Relative humidities and peak wind speeds averaged 18 percent and 10 miles per hour, respectively, during the burning period between 12:00 to 16:00 (Table 2).

BELL FIRE, Plumas National Forest, September 22, 2005 T24N, R 8E, Sec 9

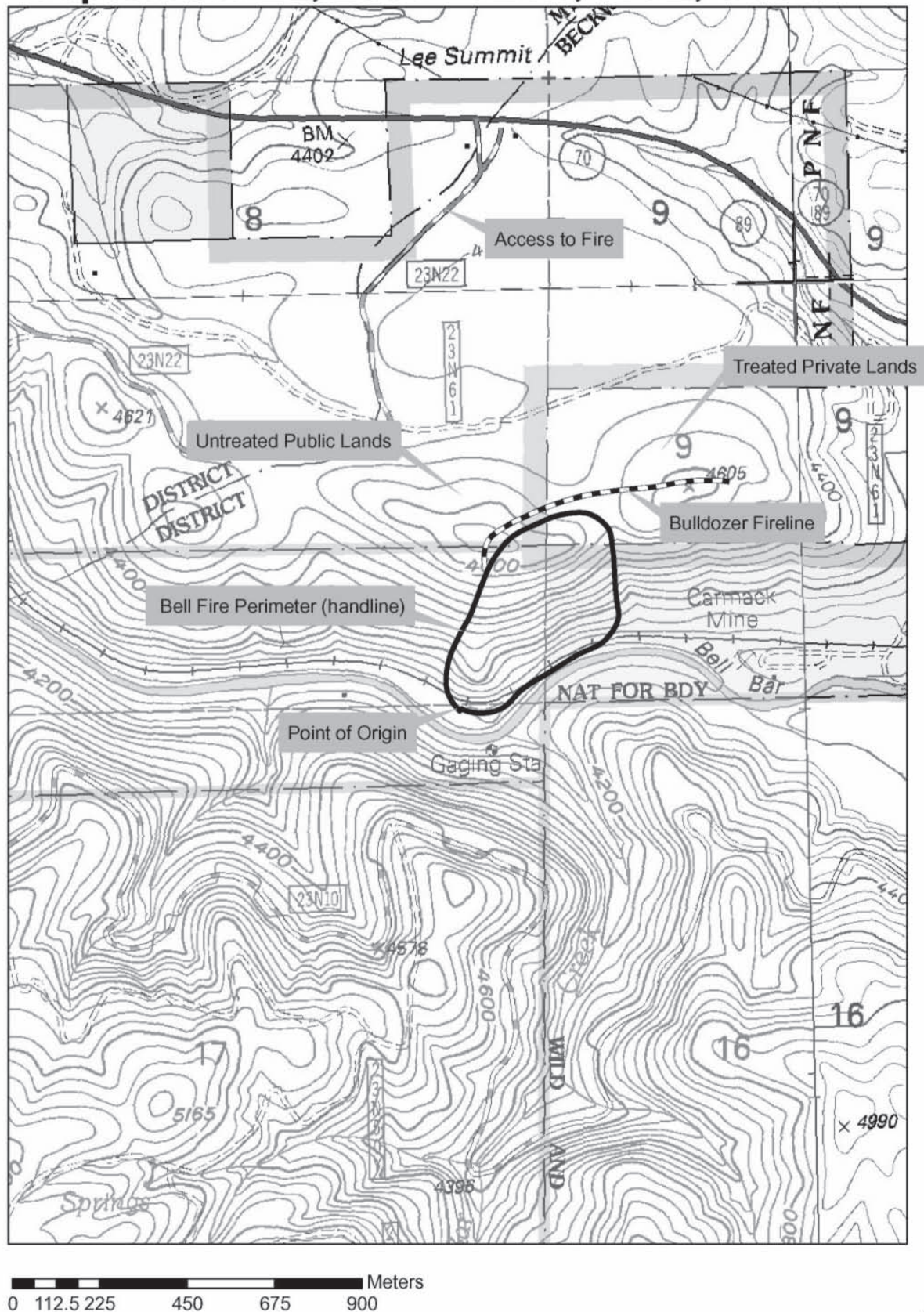


Figure 1—Location of treated area and fire perimeter



Figure 2—Treated stands (foreground) and untreated stands on public land (background). Property line follows edge of thinned area

Table 1—General fire information

Fire Name	Bell Fire
Location	Plumas National Forest, Beckworth Ranger District: T 24N, R 8E, Section 9
Elevation	4,125 ft to 4,605 ft
Burning Index on day of fire	61
Energy Release Component on day of fire	57
Report Date and Time	09/22/2005 at 12:13
Contain Date and Time	09/22/2005 at 19:00
Control Date	09/24/2005 at 18:00
Cause	Ignition from railroad activity
Final Size	35 acres

Table 2—Weather parameters during active burn period on 09/22/2005. Weather taken from Quincy remote access weather station (#40910).

Time	Relative Humidity	Dry Bulb Temperature	10-hour Fuel Moisture	Fuel Temperature	Peak Windspeed	Wind Direction
	<i>Percent</i>	<i>°F</i>	<i>Percent</i>	<i>°F</i>	<i>mi/hr</i>	<i>degrees</i>
12:00	25	74	8.9	74	6	260
13:00	18	85	8.7	103	6	144
14:00	15	86	8.0	101	14	224
15:00	14	85	7.5	98	13	243
16:00	17	82	7.2	93	17	267
17:00	21	79	7.1	81	12	256
18:00	23	75	7.0	78	11	256
19:00	31	67	7.0	63	7	259

Results

Post Treatment Stand Structure

Mechanical treatments resulted in a relatively open stand with vertical and horizontal separation of ladder and crown fuels (Figure 2). Treatments reduced the percent species composition of white fir (Table 3). Treatments raised the average height to crown base and reduced canopy cover, basal area, and overall stand density (Table 4). Though surface fuels were not treated, residual 1, 10 , and 100 hour fuels combined averaged 5.3 tons per acre (Table 5). Fuel depth average 1.4 inches (Table 5). There was no evidence of brush on the plots at the time of measurement.

Predicted and Actual Fire Behavior

The fire moved quickly up a steep hill from the point of origin to the ridgeline which was also the boundary of the fuel treatment. At the ridgeline, flame lengths from torching trees were observed as high as 30 feet above the tree canopy. Trees on the slope between the ridgeline and the point of origin generally had over 75% scorch. This level of scorch was observed on trees over 20 inches in diameter. From the point the fire impacted the fuel

Table 3—Percent species composition of conifers and hardwoods before and after treatment^a.

Species	Pretreatment	Post Treatment
----- Percent -----		
Douglas-fir	21	41
Incense cedar	18	21
Ponderosa pine	19	20
Sugar pine	10	12
White fir	29	6
Black oak	2	na

^aNote: pre and post treatment data collected within the same stand but from different plots

Table 4—Post treatment vegetation structure

	Live Trees	Basal area per acre	Height to live crown base	Tree Height	Canopy Cover	Quadratic Mean Diameter	Stand Density Index
	<i>Trees per acre</i>	<i>Ft²/acre</i>	<i>-----Feet-----</i>	<i>-----</i>	<i>Percent</i>	<i>Inches</i>	
Post Treatment Average	73.3	103.3	30.1	72.5	36.3	15.6	130.3
Post Treatment Range	40 to 130	73.2 to 154.3	24.9 to 40.2	59.0 to 84.0	25 to 48	11.9 to 18.3	105.5 to 171.1

Table 5—Post treatment fuel characteristics

	Litter & Duff	All 1, 10, and 100 hour fuels	1,000 hour sound	1,000 hour rotten	Fuel Depth	Cover of Brush
	<i>-----</i>	<i>Tons per acre</i>	<i>-----</i>	<i>-----</i>	<i>Inches</i>	<i>Percent</i>
Average	73	5.3	1.9	0.6	1.4	0
Range	19.5 to 110.5	1.3 to 8.3	0.9 to 2.8	0.0 to 0.9	0.5 to 2	0

treatment and approximately 200 feet into the fuel treatment, the level of scorch decreased. Similar patterns of scorch were observed in the Cone Fire at Blacks Mountain Experimental Forest (Skinner and others in press).

Up to four spot fires were ignited within the fuel treatment area. These fires ignited directly in activity fuels left after the harvest. Predicted flame lengths and mortality for these spot fires are shown in table 6. Observed flame lengths on these spot fires was less than 2 feet and there was little evidence of scorch on trees larger than 10 inches DBH.

The actions taken for suppression of the fire are based on discussions with on-scene personnel (Craggs 2006) and summarized here. Hand crews hiked into the base of the fire along the railroad tracks, anchored their fireline and continued constructing line up the east and west fire flanks. The Incident Commander (IC) and two bulldozer transports could access the main fire from Highway 89, along a dirt road, and directly through the treated area. From this point, the IC could also easily locate established spot fires. Due to relatively low rates of spread and flame lengths, the decision was made to line spot fires using the bulldozer. After lining the spot fires, the bulldozers then cut a line between the approaching fire front, the untreated USFS land, and the treated private property. The dozer line between the main fire and untreated USFS land was completed prior to the main fire reaching the ridge. When the fire reached the main ridge and the fuel treatment, torching stopped though direct scorch still occurred within the first 200 feet of the treatment. Finally a water tender and “pumpkin” were brought forward into the treated area and used in conjunction with engines to extinguish and mop up the spot fires. Mop up continued the next day.

Table 6—Predicted fire behavior and mortality

	Flame Length	Torching Index	Crowning Index	Predicted Mortality Trees 1 to 10 inches	Predicted Mortality Trees 10 to 20 inches	Predicted Mortality Trees 20 to 30 inches
	<i>Feet</i>	<i>--- Miles Per Hour---</i>		<i>----- DBH -----</i>		
Predicted	3.2	>40	>40	60	14	5

During the active suppression period, aerial retardant was being delivered to the area between the main fire and both the private treated area and the untreated US Forest Service property. Based on visual observations, substantially more retardant reached surface fuels in the treated area than on the untreated USFS lands. Within untreated areas, retardant was evident on upper foliage of dominant and co-dominant trees where it would not help slow the spread of surface fire.

Discussion

The treatments utilized principles of fuel reduction including thinning from below and use of whole tree harvest (Skinner and Agee 2005). While no further treatment of activity fuels generated by the harvest were completed, residual, post treatment fuel loads and arrangement resulted in observed flame lengths in spot fires was less than 2 feet. These low flame lengths in conjunction with relatively high crown base heights resulted in limited observed scorch in spot fire areas at the time of measurement. Spot fires were easily lined and allowed to burn out while suppression resources were concentrated on the main fire flanks.

In terms of suppression tactics, the treated area established a safe access point which could be use to move equipment and other resources towards the head of the main fire. Had this area not been in place, crews would have likely had to hike in an additional $\frac{1}{4}$ to $\frac{1}{2}$ mile. This would have resulted in the use of indirect suppression methods, leading to increased suppression intensity than the direct control methods utilized. The relative openness of the stand allowed the Incident Commander (IC) to maintain visual contact with equipment and personnel. In addition, greater penetration and coverage of aerial retardant to surface fuels was observed in the treated areas adjacent to un-treated areas. In untreated areas, retardant primarily ended up in the upper tree crowns where it was less effective at containing and reducing surface fire spread. The overall results of this treatment were decreased suppression intensity and increased suppression effectiveness. This in turn resulted in decreased damage to the stand due to suppression activities and direct scorch. In turn, these factors decreased the relative total cost of suppression and follow up rehabilitation.

Conclusion

It is important to emphasize that fuel treatments are not designed to stop all fires the purpose of this work is not to make this assertion. Fuel treatments are typically designed decrease flame lengths, fire spread, and ideally, reduce landscape level fire severity (Stratton 2004; Finney 2001). Often, they are to be used in conjunction with suppression resources (Agee and others 2000). This is an important point to bring out when communicating the potential effectiveness of fuel treatments with the public. Not all fuel treatments will work all the time in all vegetation types or weather conditions. Breaking up vertical and horizontal continuity of live and dead fuels in this particular case reduced passive crown fire within treated areas. Decreased flame lengths and visual contact in treated areas allowed more direct suppression methods to be employed. It is difficult to say how big the fire would have been without treatments in place or if in indirect methods were used but based on discussions with personnel on-scene, suppression intensity and cost were decreased by these treatments. If the fire had become established in the un-treated areas, suppression intensity, cost, and follow up rehabilitation would have likely been higher.

Fire managers should be able to easily document their direct experiences with fire behavior within established fuel breaks. Fire fighters are often the only ones to witness “real time” fire behavior within fuel treatments- their direct observations and experiences are critical in determining when fuel treatments work and don’t work, and how they can be modified to be more effective in the future. This is imperative considering the limited funds available for establishing fuel treatments in comparison to the number of acres that need treatment. If documented and available for public access, these observations may inform the research community of sites for possible future studies of fire behavior as well as inform and refine current hypothesis used for these studies. This information will help provide the necessary feedback for changing and improving practices through adaptive management.

Acknowledgments

Thanks to Paul Violett and the Soper-Wheeler Company for allowing access to their land and records for this study. Special thanks to Larry Craggs, Fire Management Officer, and Ryan Southwick, Dozer 2 Operator both from the Mount Hough Ranger District on the Plumas National Forest. Their eyewitness experiences on this fire were essential in conveying the story of what happened as seen by the folks who were there as it burned.

References

- Agee, James K., Bahro, Berni, Finney, Mark A., Omi, Phillip N., Sapsis, David B., Skinner, Carl N., van Wagendonk, Jan W, and Weatherspoon, Phillip C. 2000. The use of shaded fuel breaks in landscape fire management. *Forest Ecology and Management* 127:55-66.

- Beckman, Sid. 2001. Assessment of the effects of multiple fuel treatments on fire spread and timber stand damage: Stream Fire, Plumas N.F., July 26th, 2001. Fire Behavior Analyst, California Interagency Incident Management Team 5.
- Callenberger, Barry and Lunder, Zeke. 2006. Plumas County Hazardous Fuel Assessment Strategy. January 20, 2006; 58 p.
- CDF (California Department of Forestry and Fire Protection). 2003. The California Forest Practice Rules. Sacramento, CA: The California Department of Forestry and Fire Protection, Resource Management, Forest Practice Program; 202 p.
- Dunning, Duncan. 1942. A Site Classification for the Mixed-Conifer Selection Forests of the Sierra Nevada. Forest Research Note 28; USDA Forest Service California Forest and Range Experiment Station; 21 p.
- Finney, Mark A. 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *Forest Science* 47(2): 219–228.
- Fites, Jo Ann and Henson, Carol. 2004. Real-time evaluation of effects of fuel-treatments and other previous land management activities on fire behavior during wildfires. Final Report of the Joint Fire Sciences Rapid Response Project. September 20, 2004; 13 p.
- Healthy Forests Report. 2005. Healthy Forests Report. www.healthyforests.gov/projects/healthy-forests-report-final.pdf. 5 p.
- Hood, Larry D. 1999. A defensible fuel profile zone gets put to the test. Memo: Larry Hood, Team Member, Adaptive Management Services, Rapid Response Fire Planning and Analysis Team. 3 p.
- PCFSC (Plumas County Fire Safe Council), 2005. Plumas County Communities Wildfire Mitigation Plan. February, 2005; 10 p.
- Skinner, Carl N., Ritchie, Martin W., Hamilton, Todd, and Symons, Julie. In Press. Effects of prescribed fire and thinning on wildfire severity: The Cone Fire, Blacks Mountain Experimental Forest. *Proceedings 25th Vegetation Management Conference*, Jan. 2004, Redding, CA; 12 p.
- Stephens, Scott L. and Ruth, Larry W. 2005. Federal forest fire policy in the United States. *Ecological Applications*, 15(2):532-542.
- Stephens, Scott L. and Moghaddas, Jason J. 2005(a). Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a mixed conifer forest. *Forest Ecology and Management*, 215:21-36.
- Stephens, Scott L. and Moghaddas, Jason J. 2005(b). Silvicultural and reserve impacts on potential fire behavior and forest conservation: 25 years of experience from Sierra Nevada mixed conifer forests. *Biological Conservation*, 25:369-379.

Personal Communications

- Craggs, Larry. 2005. Fire Management Officer, Mount Hough Ranger District, Plumas National Forest.
- Violett, Paul. 2005. Forester, Soper-Wheeler Company.

The Use of Silviculture and Prescribed Fire to Manage Stand Structure and Fuel Profiles in a Multi-aged Lodgepole Pine Forest

Colin C. Hardy¹, Helen Y. Smith², and Ward McCaughey³

Abstract—This paper presents several components of a multi-disciplinary project designed to evaluate the ecological and biological effects of two innovative silvicultural treatments coupled with prescribed fire in an attempt to both manage fuel profiles and create two-aged stand structures in lodgepole pine. Two shelterwood silvicultural treatments were designed to replicate as well as enhance the existing multi-aged stand structure on the Tenderfoot Creek Experimental Forest in central Montana: the first, with reserve trees evenly distributed; the second, with reserves contained within small (1/10-1/4 acre) groups. Retention of reserve trees was targeted at 50%, without regard to diameter or species. Eight even distribution and eight group-retention treatments were applied on 16 units totaling 649 acres. Half of the units were broadcast burned following harvest using a common burn prescription on all units. Allowable overstory mortality specified in the prescribed fire plan was 50%. Plot-based fuel inventories and fire effects observations were performed at permanent plot locations prior to and following harvest, and after burning. Fuel moisture samples were acquired immediately prior to ignition. Data from four prescribed-burned treatment units were evaluated for this paper: two even-retention units and two grouped retention units. Harvest activities resulted in significant increases in fine-fuel loading (1-, 10-, and 100-hour fuel), which was subsequently reduced by prescribed fire to near pre-harvest levels. Consumption of large woody fuel was similar for both treatment types. The fire-induced mortality of overstory trees was greater in the even distribution than in the grouped distribution. Despite careful execution of a relatively conservative burn plan, mortality in the even treatments exceeded the prescription threshold of 50% by an additional 28%. Additional data collected at the plots include trees per acre, residual tree mortality, residual tree growth, regeneration, windthrow, hydrologic responses, soil impacts, and beetle activity. A comprehensive summary of the treatments will follow subsequent monitoring scheduled to occur five and ten years after burning.

Introduction

The Tenderfoot Research Project is a multi-disciplinary effort designed to evaluate and quantify the ecological and biological effects of innovative restoration treatments in an attempt to both manage fuelbed profiles and create two-aged stand structures in lodgepole pine. The suite of sixteen fire and silvicultural treatments were implemented on the Tenderfoot Creek Experimental Forest (TCEF) in the Little Belt Mountains of central Montana (fig. 1). Although the USDA Forest Service has established seventy-seven experimental forests and ranges, the TCEF is the only reserve dominated by the lodgepole pine forest type (Adams and others 2004). The research presented here was guided by the Tenderfoot Creek Research Project mission (USDA Forest Service 1997):

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

¹ Project Leader, Fire Behavior Research Work Unit, USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Missoula, MT. chardy01@fs.fed.us

² Ecologist, Fire Ecology and Fuels Research Work Unit; Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Missoula, MT.

³ Research Forester, Ecology and Management of Northern Rocky Mountain Forests Research Work Unit, Rocky Mountain Research Station, Missoula Forestry Sciences Laboratory, Missoula, MT.

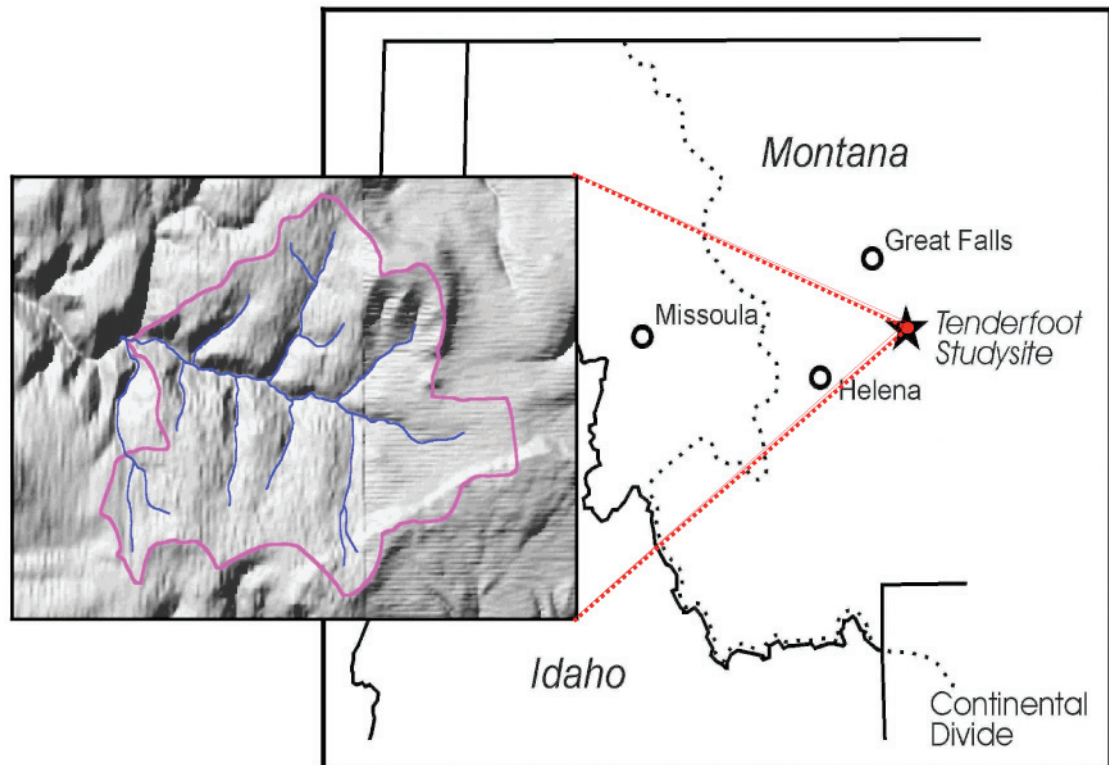


Figure 1—The Tenderfoot Creek Experimental Forest is a 9,125 acre watershed located in Central Montana.

“Test an array of management treatments for regenerating and restoring healthy lodgepole pine forests through emulation of natural disturbance processes, but avoiding catastrophic-scale disturbances.”

This paper documents a preliminary exploration of selected results following completion of all phases of treatment activities. It is our intent to follow this paper with a comprehensive compilation of results that synthesize all aspects of the multi-disciplinary efforts.

Background

The subalpine lodgepole pine forest type is estimated to cover about 15 million acres in the western United States and a much larger area (nearly 50 million acres) in western Canada (Lotan and Critchfield 1990). Its latitudinal range extends from Baja (35° latitude) to the Yukon (65° latitude), and longitudinally from the Pacific coast to the Black Hills of South Dakota. In the Rocky Mountains of the Interior West, lodgepole pine is the third most extensive forest type. The adaptations of lodgepole pine to severe, stand replacement fire—in particular its serotinous cones—have long been acknowledged (Lotan and Perry 1983). Less well-known is that lodgepole pine forests also burn in low- to mixed-severity fire, often creating two-aged stands and variable patterns across the landscape (Agee 1993; Arno 1980; Barrett and

others 1991). Numerous studies in the interior Northwest have documented the intricate mosaic patterns of historical fires in lodgepole pine forests (Arno and others 1993; Barrett 1993; Barrett and others 1991). Newer studies are looking more closely at the details of these patterns and their implications for management (Hardy and others 2000; Stewart 1996). These studies are being used as a basis for designing and refining silvicultural and prescribed fire treatments in National Forests of the Northern Rocky Mountains.

Historically, clearcutting and broadcast burning of lodgepole pine forests was considered to be economically efficient and conducive to regeneration. These treatments roughly mimic effects of natural, stand-replacement fires. More recently, foresters have recognized that burning irregularly shaped cutting units containing patches of uncut trees, while also creating snags, would far more effectively simulate effects of historical fires. One negative effect from leaving patches or individual uncut trees in lodgepole pine forests is the vulnerability of the species to windthrow. However, recognition of the extent of the mixed-severity fire regime in lodgepole pine, and the recent success and experience gained from other pilot projects have led to continued efforts toward more ecologically-based management of lodgepole pine.

Paired watersheds at TCEF have been monitored for several years and serve as a basis for comparison of water quantity and quality under different cutting and burning treatments. A detailed fire history study and map completed by Barrett (1993) documents a sequence of stand replacement and mixed-severity fires extending back to 1580 (fig. 2A). Stand-replacing burns occurred at intervals of 100 to over 300 years, with low- or mixed-severity burns often occurring within these intervals. Two-aged stands cover about half the area at TCEF, ranging in size from a few acres to about 1,000 acres (fig. 2B). Experimental treatments at TCEF were designed to reflect these historical disturbance patterns. The study design for TCEF integrates observations of on-site treatment response with water yield and water quality data from paired, experimental sub-watersheds that have monitoring flumes.

In this paper we present new research and preliminary results specifically related to fuel management that may lead to more complete knowledge and innovative techniques to manage lodgepole pine forests in the Interior West.

Methods

Timeline for Planning and Execution

The timeline for execution of the study is given in table 1. The Tenderfoot Creek Experimental Forest is administered by the Rocky Mountain Research Station (RMRS) in collaboration with the Lewis and Clark and National Forest. Research is proposed and planned by RMRS and timber sales on the EF are conducted and administered by the National Forest. Implementation of any research on the Experimental forest requires close and continuous cooperation between research and National Forest personnel.

Planning for this extensive study was initiated by Forest Service Research in 1995, and an interdisciplinary planning team was assembled by the Lewis and Clark National Forest to accomplish the Environmental Assessment (EA) process required for the project. The EA was completed in 1998 and a final decision notice was issued in early 1999. Construction of approximately 2 ½ miles of roads was accomplished in 1999, with harvesting completed in 2000. Prescribed burning operations were executed in 2002 and 2003.

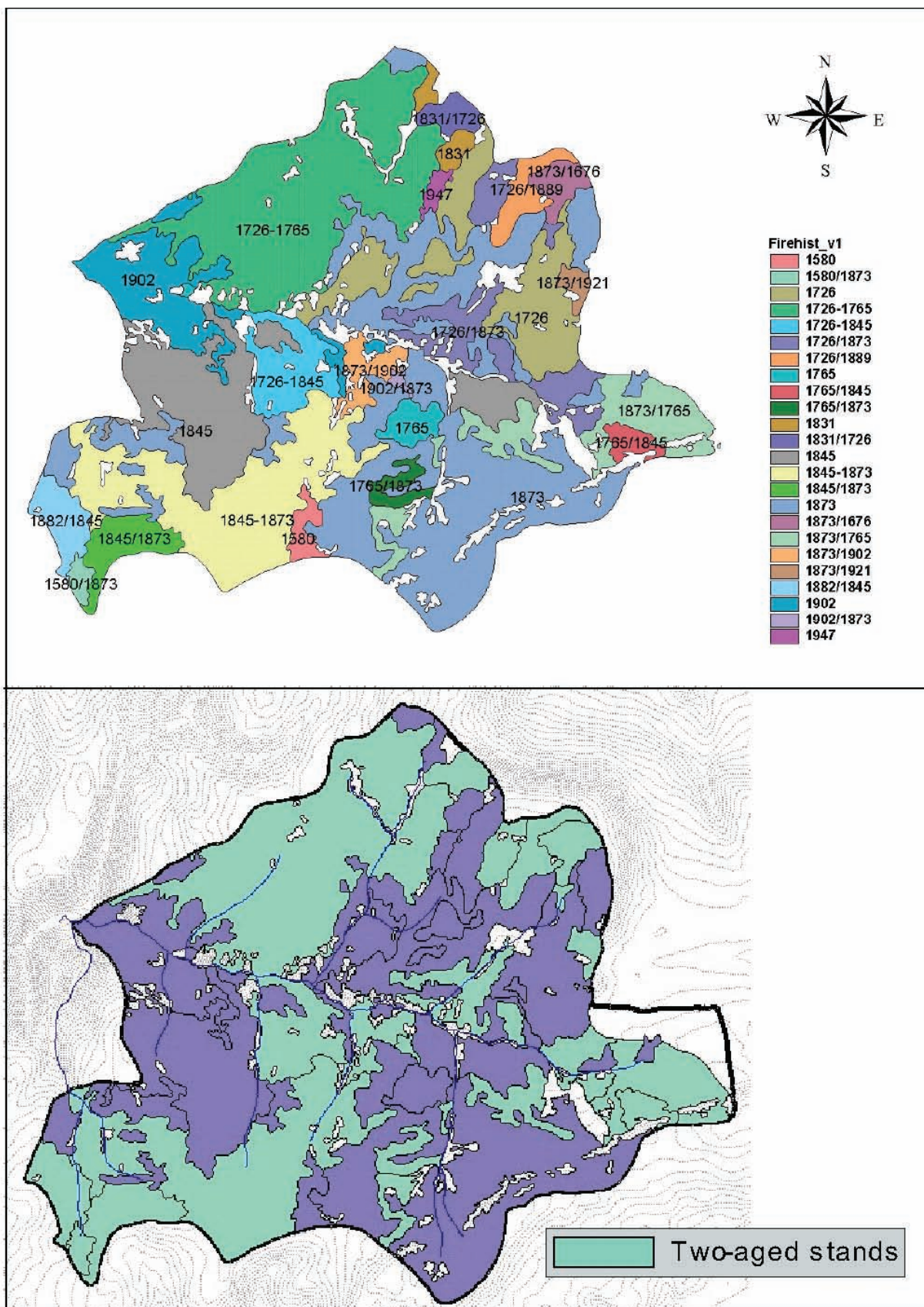


Figure 2—An extensive fire history study done at TCEF in 1986 documented a complex mosaic of fires dating back to 1580 (top), and determined that about half of TCEF is comprised of two-aged stands resulting from low- to mixed-severity fire(s).

Table 1—Timeline of activities, from project proposal to post-burn assessments.

Date(s)	Activity
1995 – 1997	Draft Research Proposal MOU between FS Research and L&C Nat'l Forest
1997 – 1998	Planning with L&C Nat'l Forest Scoping/public comment
Spring 1999	Environmental Assessment
1999 – 2000	Establish treatment units Sale administration Road installation Pre-harvest sampling Harvest activities Prepare burn prescriptions
Autumn 2001	Burn all piles and windrows
Summer 2002	Post-harvest sampling
2002 – 2003	Burn treatments
2003 – 2005	Post-burn sampling and assessments

Treatment Descriptions and Locations

The large-scale set of treatments were implemented on two sub-watersheds within the 9,125-acre Experimental Forest, with two adjacent sub-watersheds left as untreated controls. The two treatment sub-watersheds are Spring Park Creek (north of Tenderfoot Creek) and Sun Creek (south of Tenderfoot Creek) (fig. 3). The silvicultural system used was a two-aged system termed “shelterwood with reserves,” with two forms of leave tree retention: one with leave trees evenly distributed, and the other with leave trees retained in unharvested retention groups distributed across the treatment units in a noticeably uneven pattern. The harvest system utilized in all units included felling by excavator-mounted “hot saws” and whole-tree skidding to centralized processing locations where the trees were de-limbed and decked for transport. All unutilized materials were piled and burned on site. About 50 percent of the basal area and stems were removed in both treatment types, with low intensity underburns in one-half of the treatment units. One objective for low intensity underburns was mitigation of surface fire hazard exacerbated by high loadings of harvesting debris (slash). The fuelbed components most relevant to a hazard reduction objective are the fine fuels: 1-hour, 10-hour, and 100-hour timelag fuelbed components. It is these fuel particles that contribute most significantly to surface fire behavior, and a reduction in loading of these fuelbed components was a principle objective in the treatment prescription. The sum of these three fuelbed components is hereafter referred to as “fine-fuel loading.”

The treatment labels and descriptions are summarized in table 2, and a satellite (IKONOS®) image of the two Sun Creek treatments is shown in figure 4.

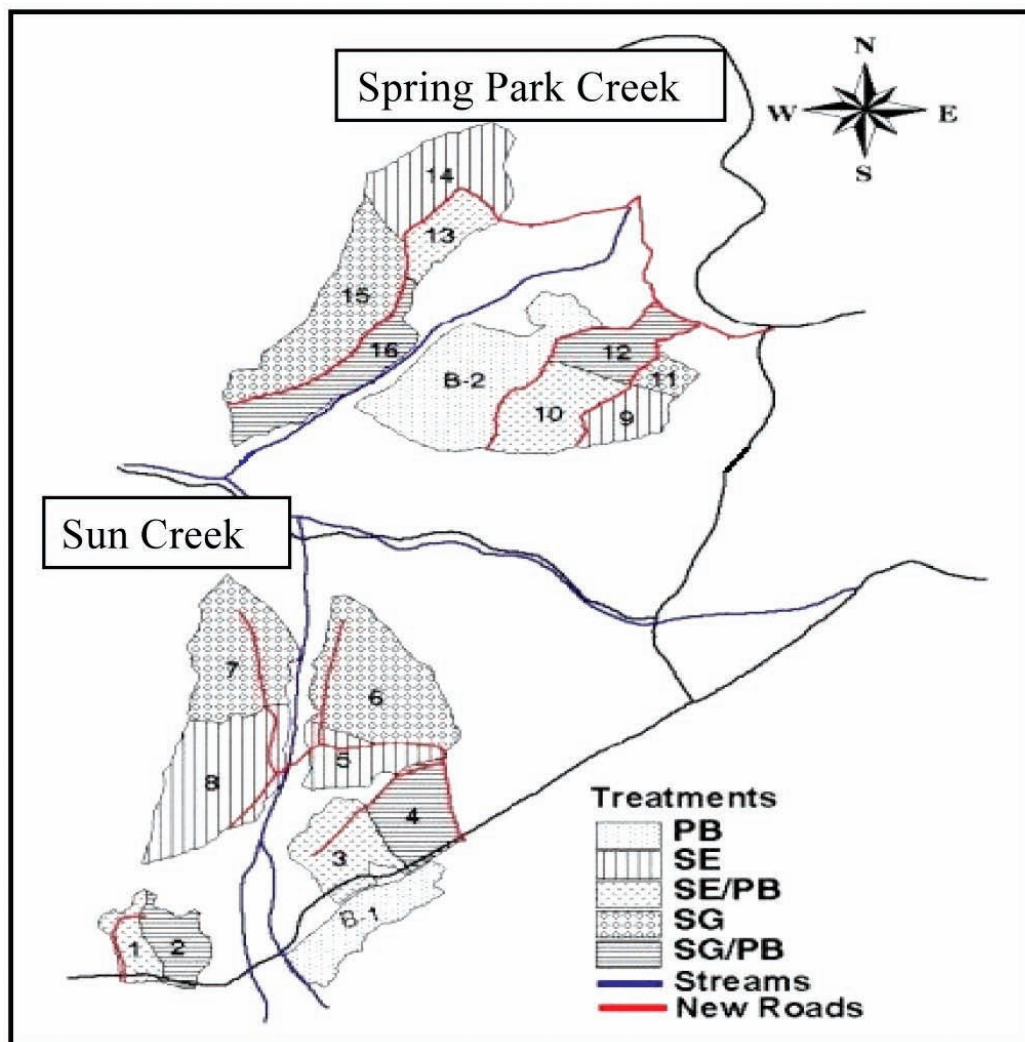


Figure 3—Treatment units were located in two sub-watersheds of Tenderfoot Creek: Spring Park Creek (south aspect, north of Tenderfoot Creek), and Sun Creek (north aspect, south of Tenderfoot Creek).

Table 2—Treatment labels and descriptions.

Treatment label	Distribution of retention trees	Prescribed fire
SE	Evenly distributed	None
SEB	Evenly distributed	Burned (B)
SG	Group-retention	None
SGB	Group-retention	Burned (B)

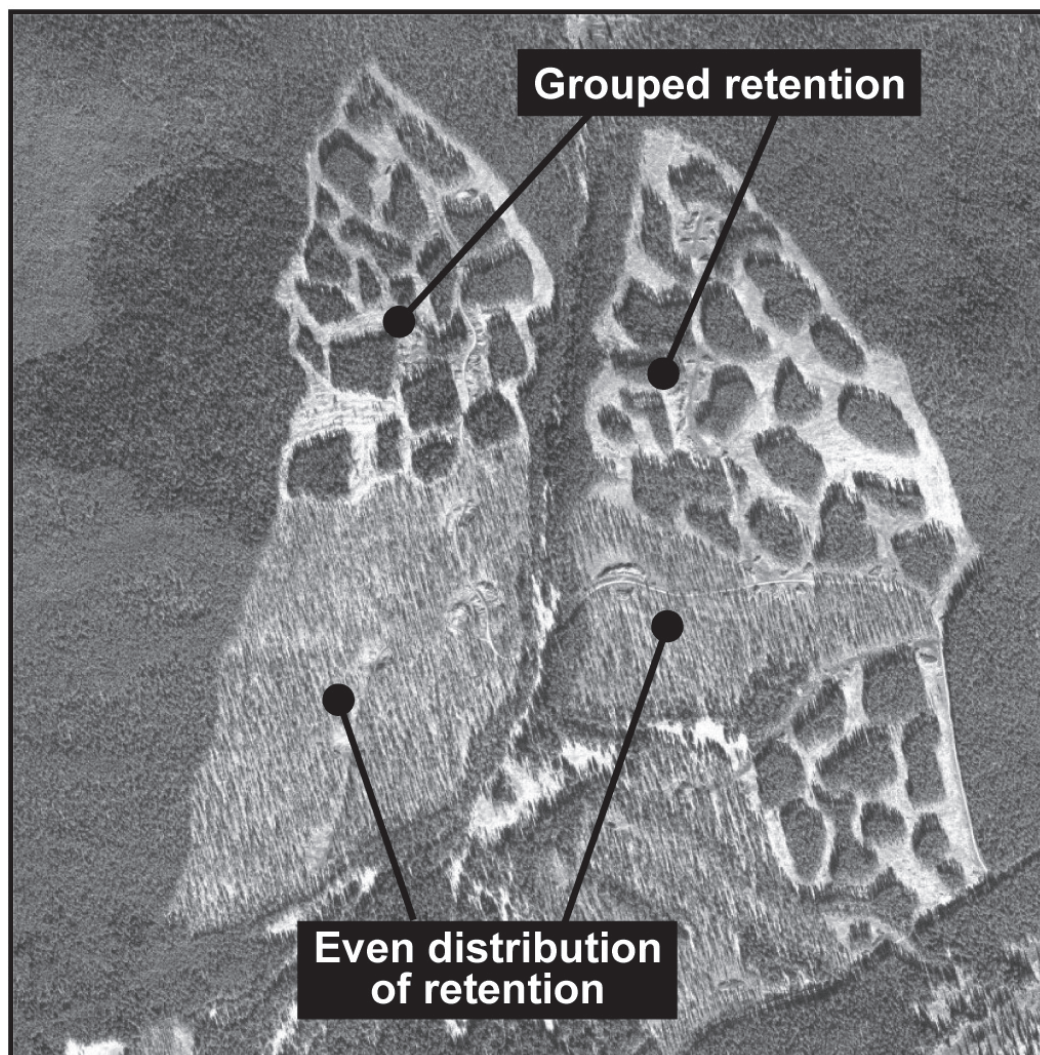


Figure 4—An IKONOS® satellite image showing the two types of “shelterwood with reserves” silvicultural treatments.

Field Sampling

The average size per treatment unit was 43 acres. An average of 32 sampling plots per unit (about one plot per 1.3 acres) were permanently located to facilitate multiple-year sampling at each plot—pre-harvest, post-harvest, and post-burning. In addition to a comprehensive assessment of vegetation and stand characteristics, fuelbed data were collected on one-half of the plots, where two 75' line-intercept fuel transects were installed and permanently located at each plot. Fuel loadings (mass per unit area) of all fuel components along each transect were then estimated per Brown (1974). This allows the generation of summary statistics and analyses that can be calculated at multiple levels—plot, unit, and treatment type (pooled-unit).

The consumption by prescribed burning of large woody fuel was determined by measuring the reduction in diameter of sampled logs using wires installed prior to burning. Following burning, the wires were tightened, and the difference in wire length was used to determine reduction in diameter and associated mass.

Following burning, annual assessments will continue for several years to document windthrow (a problem common to lodgepole pine) and both fire- and insect-caused tree mortality. The burn prescription for both the *Even* and *Grouped* treatment type specified a maximum target overstory tree mortality of fifty percent. Data from three years of post-burn mortality sampling are available for the present analysis.

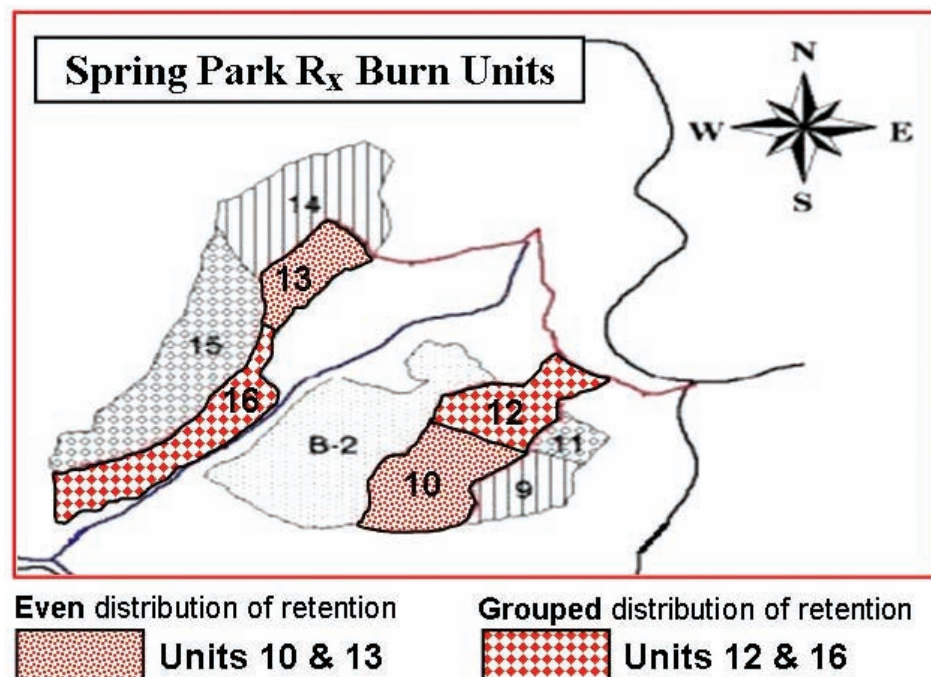
Analysis

Although the study included treatment units in both Spring Park Creek and Sun Creek sub-watersheds, we did not obtain pre-harvest sample data from the Sun Creek Units. Therefore, fire- and fuels-related data spanning all phases of the study (pre-harvest, post-harvest, and post-burn) are only available for Spring Park Creek.

The fuels analysis in this paper is focused on the four treatment units within Spring Park Creek that included prescribed burning following harvest (SEB and SGB). This selection constraint for the current analysis provides two pairs of treatment units: one pair of *Even* distribution with burning (SEB—units 10 and 13), and one pair of *Grouped* retention with burning (SGB—units 12 and 16). The Spring Park Creek units are illustrated in figure 5.

Prior to pooling the fine-fuel loading data from pairs of units, we evaluated the individual unit statistics to ensure similarity of variances and central tendencies between units within a pooled pair. This analysis was done for each of pre-harvest, post-harvest, and post-burn fine-fuel loading data. The box-and-whisker plots given in figure 6 present median values and interquartile ranges (expressed as tons per acre), and also illustrate the 0.05 *Student's t* statistic. We can conclude from the plots in figure 6 that no significant difference existed in fine-fuel loading between pairs of units in either the *Even* retention pool (fig. 6A) or *Grouped* retention pool (fig. 6B). Therefore, results will be presented with respect to the pooled classes.

Figure 5—Two pairs of units in Spring Park were selected for analysis: SEB (units 10 & 13), and SGB (units 12 & 16).



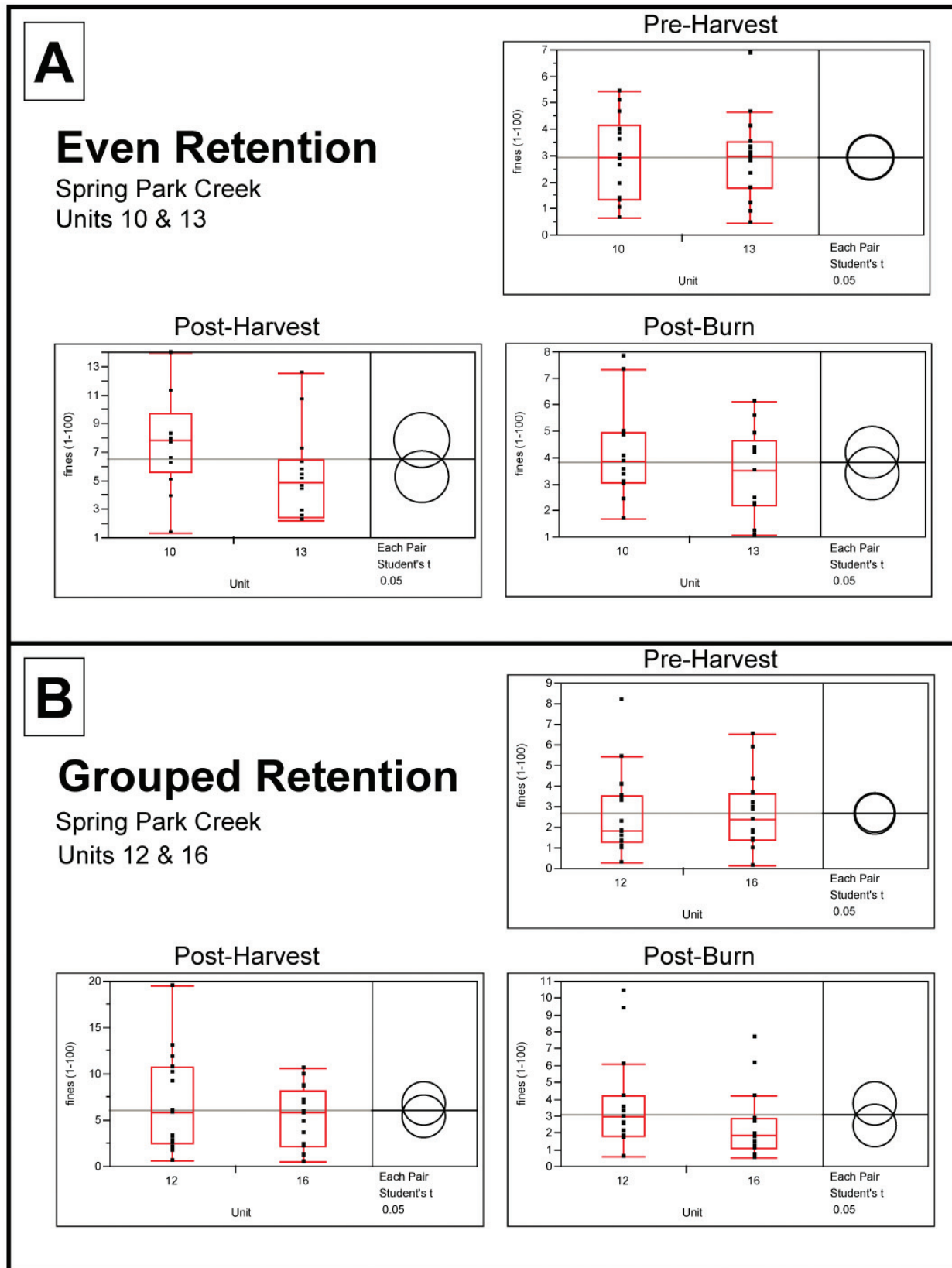


Figure 6—Median values, interquartile ranges, and the 0.05 *Student's t* statistic (expressed as tons per acre) presented as confirmation that fine-fuel loadings in the pooled units are not significantly different for either the Even (6A) or Grouped (6B) treatments.

Results

We present results of preliminary analyses by comparing pre-harvest, post-harvest and post-burn conditions between the two harvest-and-burn treatments on Spring Park Creek. As described above in methods, two treatment units are pooled for each of the two treatment types—SEB and SGB. Results presented here are limited to fine-fuel loading, large-woody fuel loading, and fire-caused overstory tree mortality.

Fine-Fuel Loading—Harvesting activities contributed approximately 3.5 tons per acre of fine fuels in both the *Even* and *Grouped* treatments, as illustrated in figure 7 by the mean values of all plots within the pooled units for each treatment type—this is roughly a one hundred percent increase from pre-harvest conditions (fig. 7). The prescribed burning treatment following harvest reduced the fine-fuel loading to near pre-harvest conditions in both treatment types; reductions were 2.7 tons per acre and 3.0 tons per acre for the *Even* and *Grouped* treatments, respectively. While the post-harvest fine-fuel loadings were significantly higher ($\alpha=0.05$) than either the pre-harvest or post-burn loadings for both treatment types, the differences between pre-harvest and post-burn fine-fuel loadings were not statistically significant ($\alpha=0.05$) for either treatment type. In summary, the harvesting activities resulted in significant increases in fine-fuel loadings, and post-harvest prescribed burning effectively reduced the fine-fuel loadings to pre-harvest levels.

Large Woody Fuel Loading—We compared the consumption (mass reduction measured in tons per acre) of large woody fuel due to prescribed burning between the *Even* and *Group* treatment types. Mean values and 95% confidence intervals representing all plots within the pooled units for each treatment type are presented in figure 8. In both treatment types, less than one ton per acre of large woody fuel was consumed, with no significant difference between the treatment types ($\alpha=0.05$) (fig.8). The percent mass reduction in large woody fuels for the *Even* and *Group* treatment types was

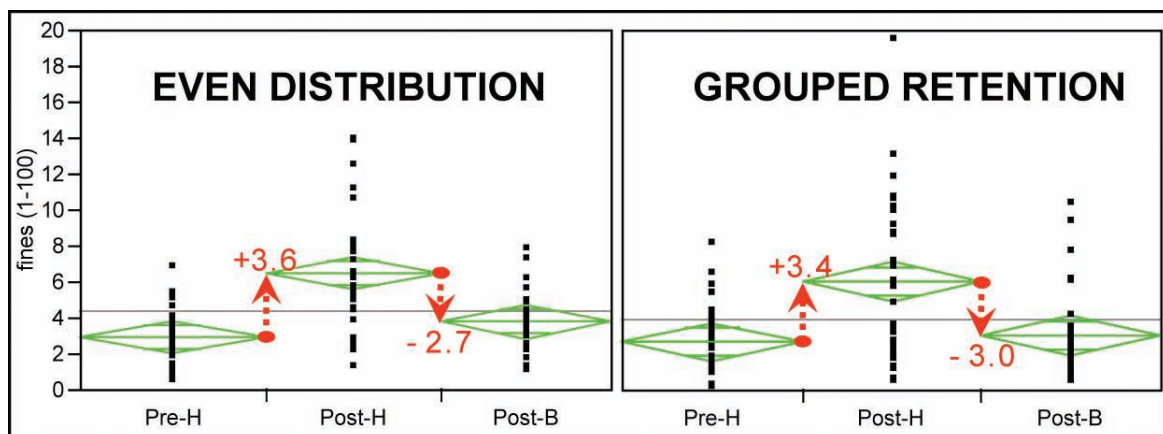


Figure 7—Changes in fine-fuel loading (tons/acre) between pre-harvest, post-harvest, and post-burning for pooled *Even* (left) and *Grouped* (right) distribution units.

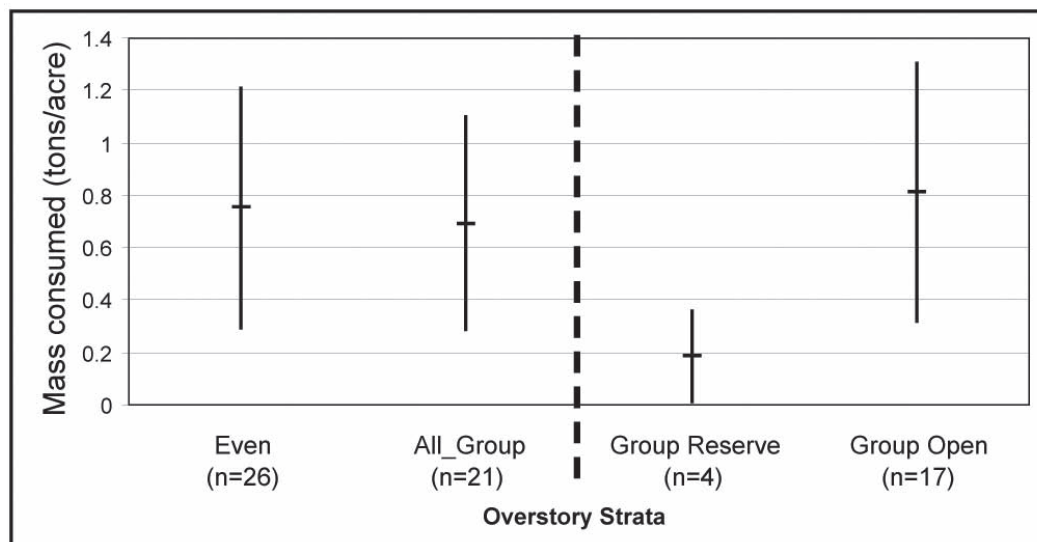


Figure 8—Comparison of means and 95% confidence intervals for consumption of large woody fuel (1000-hour) between Even and Grouped (*All_Group*) distributions. The data labeled “*Group Reserve*” are from plots within the grouped retention areas, and data labeled “*Group Open*” are from plots located in the open (harvested) areas between groups.

14.5% and 12.9%, respectively. Within the grouped treatment types are two distinct distributions of overstory: 1. The un-harvested retention groups; and 2. The completely harvested (effectively, “clearcut”) open areas between grouped reserves. These two strata are labeled in figure 8 as “*Group Reserve*” and “*Group Open*,” respectively. While the total mass consumption of large woody fuel in the *Group Open* plots was somewhat greater than the average for the overall group treatment (labeled “*All_Group*” in figure 8), consumption within the *Group Reserves* was significantly lower than either the *Group Open* or the *Even* distribution ($\alpha=0.05$). In terms of percent mass reduction in large woody fuels within the two *Group* treatment strata, there was a 19.5% reduction in mass for the *Group Open* strata and only a 2.7% reduction for the *Group Reserves* strata.

Fire-induced Overstory Tree Mortality—Although most of the results presented here have been confined to the Spring Park treatments, data on fire-induced overstory tree mortality were acquired and analyzed for treatments in both Spring Park Creek and Sun Creek. Mortality data from each of the first three years following burning are presented in figure 9. Within a treatment type (*Even* or *Group*) the three-year trends are similar for both sub-watersheds. However, a general comparison of mortality between the two sub-watersheds indicates higher levels of mortality in the Spring Park units, regardless of treatment type (fig. 9). By the third year following burning, mortality in the *Even* treatments was twenty-three percent and thirty-seven percent higher than for the *Group* treatments in Sun Creek and Spring Park, respectively. The highest mortality, seventy-eight percent, was observed for the *Even* treatment type in Spring Park— twenty-eight percent higher than the maximum prescription target of fifty percent.

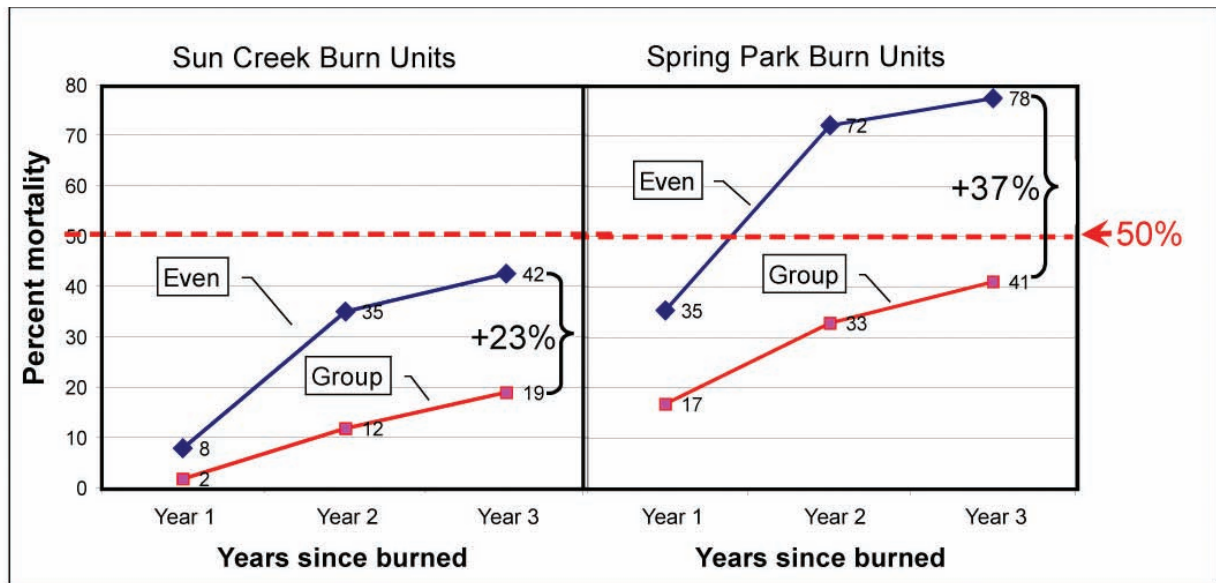


Figure 9—Fire-caused mortality was much higher for the Spring Park units than for Sun Creek; mortality for the even distribution was much higher (23%-37%) than for the grouped distribution; and in the even distribution for Spring Park mortality greatly exceeded the prescribed upper limit of 50%.

Discussion

Specific evidence presented here regarding the consequences related to two of four treatment alternatives is limited to fine-fuel loadings, consumption of large woody fuel, overstory tree mortality, and anecdotal observations. The significant increase in fine-fuel loadings resulting from harvest activities was well mitigated by post-harvest prescribed burning. Although fine-fuel loadings were effectively doubled by harvest activities, the absolute loadings were not particularly high (3.5 tons/acre). In lodgepole pine, however, the vulnerability of the thin-barked species to bole-related mortality is high, relative to most other coniferous species. This makes management of fine-fuel loadings—the principle contributor to surface fire intensity—of paramount importance. Despite very careful execution of a conservative prescribed fire plan, increased levels of fine-fuel loadings caused by the harvesting activities in the *Even* distribution treatment were high enough to cause unacceptable fire-induced mortality. During a typical wildfire season, most fuel and weather conditions would be significantly warmer, drier, and windier than conditions under which the prescribed burning treatments were applied. In such cases, the fine-fuel loadings present following the harvesting activities would lead to dramatic, unacceptable increases in overstory tree mortality. For example, the comparison of mortality between the Sun Creek units and the Spring Park Creek units shown in figure 9 indicates much lower mortality for the Sun Creek units. Despite our desire to burn all units within similar weather and fuel conditions, the relative humidity was considerably higher during the burning operations in Sun Creek, with lower temperatures and wind speeds. Although not considered in the statistical analyses, these conditions provide substantial anecdotal evidence supporting the sensitivity of the lodgepole pine forest type to fire-weather conditions.

In contrast to the prescriptions targeting reductions in fine-fuel loading through prescribed fire treatments, there is neither a fire hazard-related nor ecological advantage to burning of large woody fuel components (there are, in fact, a number of advantages to retaining large woody biomass). When the large woody fuel becomes involved in combustion, there are significant increases in heat flux to the soil and organic surface components, and also production of significantly elevated levels of smoke emissions from combustion of the large woody fuels as well as other biomass associated with the large fuel combustion. There was no significant difference in large woody fuel consumption between the two treatment types, however, so there are no management implications associated with large-woody fuel consumption.

Although there is an on-going field effort to assess and document windthrow in all treatment units, quantitative data are not yet available. However, anecdotal evidence from observations over the short period of time since completion of management activities show significant windthrow in several of the *Even* treatment units. In contrast, windthrow in the Group treatment have been observed to be limited to an occasional tree at the perimeter of the retention groups.

These preliminary results provide a first-look at the relative successes of innovative silvicultural and prescribed fire treatments targeting restoration and maintenance of lodgepole pine forest systems. They are not, however, sufficient enough to support conclusions from which to formulate management direction. The research mission for TCEF directed us to “test an array of management treatments for regenerating and restoring healthy lodgepole pine forests through emulation of natural disturbance processes, but avoiding catastrophic-scale disturbances.” Results from further examination of the complete data set from this study will be integrated with results from other Tenderfoot Creek Research Project studies in a comprehensive assessment of the feasibility and consequences of these innovative treatments. More management direction may be provided at that time.

References

- Adams, M. B.; Loughry, L.; Plaugher, L. comps. 2004. Experimental forests and ranges of the USDA Forest Service. Gen. Tech. Rep. NE-321. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 178 p.
- Agee, J. K. 1993. Fire ecology of Pacific Northwest forests. Washington D.C.: Island Press. 493 p.
- Arno, S. F. 1980. Forest fire history in the northern Rockies. *J. Forestry* 78(8):460-465.
- Arno, Stephen F.; Reinhardt, E. D.; Scott, J. H. 1993. Forest structure and landscape patterns in the subalpine lodgepole pine type: A procedure for quantifying past and present conditions. Gen. Tech. Rep. INT-294. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 17 p.
- Barrett, S. W. 1993. Fire history of Tenderfoot Creek Experimental Forest, Lewis and Clark National Forest. Contract completion report on file at the Rocky Mountain Research Station, Forestry Sciences Lab, Bozeman, MT.
- Barrett, S. W.; Arno, S. F.; Key, C. H. 1991. Fire regimes of western larch-lodgepole pine forests in Glacier National Park, Montana. *Can. J. Forestry Res.* 21:1711-1720.

- Brown, J. K. 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep. INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.
- Hardy, C.C.; Keane, R.E.; Stewart, C.A. 2000. Ecosystem-based management in the lodgepole pine zone. In: Smith, H. Y., ed. 2000. The Bitterroot Ecosystem Management Research Project: What we have learned—symposium proceedings; 1999 May 18-20; Missoula, MT. Proceedings RMRS-P-17. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 31-40.
- Lotan, J. E.; Critchfield, W. B. 1990. *Pinus contorta* Dougl. ex. Loud.-lodgepole pine. IN: Burns, R.M.; Honkola, B. H., Tech. coordinatores. *Silvics of North America: Vol. 1, Conifer. Agric. Handb.* 654,. Washinton, D.C.: U.S. Dept. of Agri. pp. 302-315.
- Lotan, J.E.; Perry, D.A. 1983. Ecology and regeneration of lodgepole pine. *Agric. Handb.* 606. Washington, DC: USDA Forest Service. 51 p.
- Stewart, C. A. 1996. Restoring historic landscape patterns through management: restoring fire mosaics on the landscape. In: Hardy, C. C.; Arno, S. F., eds. 1996. *The use of fire in forest restoration*. Gen. Tech. rep. INT-GTR-341: U.S. Department of Agriculture, Forest Service, Intermountain Mountain Research Station. 49-50.
- USDA Forest Service. 1997. Tenderfoot research project: a proposal for research and demonstration of ecosystem-based treatments in lodgepole pine forests on the Tenderfoot Creek Experimental Forest. [Unpublished report on file]. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 22 pages.

Effectiveness of Prescribed Fire as a Fuel Treatment in Californian Coniferous Forests

Nicole M. Vaillant¹, JoAnn Fites-Kaufman², Scott L. Stephens³

Abstract—Effective fire suppression for the past century has altered forest structure and increased fuel loads. Prescribed fire as a fuels treatment can reduce wildfire size and severity. This study investigates how prescribed fire affects fuel loads, forest structure, potential fire behavior, and modeled tree mortality at 80th, 90th, and 97.5th percentile fire weather conditions on eight National Forests in California. Potential fire behavior and effects were modeled using Fuel Management Analyst. Prescription burning did not significantly change forest structure at most sites. Total fuel loads (litter, duff, 1, 10, 100, and 1000-hour) were reduced by 23 to 78 percent across the sites. This reduction in fuels altered potential fire behavior by reducing rate of spread, flame length, and fireline intensity. Increased torching index values coupled with decreased fuel loads reduced crown fire potential post-treatment in some stands. Predicted tree mortality decreased post-treatment as an effect of reduced potential fire behavior and fuel loads. With the vast forested areas classified at high risk for catastrophic wildland fire in California, it is most efficient to target stands that benefit the most from treatment.

Introduction

In many coniferous forests, fire suppression has led to higher tree densities (Biswell 1959), changes in species composition (Weaver 1943), and higher fuel loads (Dodge 1972), which have altered fire regimes (Beaty and Taylor 2001; Stephens and Collins 2004). A recent analysis of fire cause and extent on U.S. Forest Service (USFS) lands from 1940 to 2000 demonstrated that California experienced a significant increase in the total number of fires and had the most area burned relative to other regions in the United States (Stephens 2005). Although the area burned has not significantly increased from 1940 to 2000 in California (Stephens 2005), the wildland fire problem has only worsened as suppression has become more effective (Brown and Arno 1991).

Fuels treatments can be effective at reducing the severity (Pollet and Omi 2002; Agee and Skinner 2005; Finney and others 2005) and size of wildland fires (Stephens 1998; Piñol and others 2005). Reduction of surface fuels, and in some cases crown fuels, can reduce the likelihood of crown fires (van Wagner, 1977). Typically, mechanical methods are used to alter stand structure (i.e., reduce tree density, decrease basal area, increase the height to live crown base, and reduce canopy cover) (Keyes and O'Hara 2002; Pollet and Omi, 2002; Stephens and Moghaddas, 2005a,b). Prescribed fire alone can decrease surface and ladder fuels which reduce potential fire behavior and thus lower the risk of crown fire and spot fire ignition (van Wagtenonk 1996; Stephens 1998).

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

¹ Graduate student at UC Berkeley and a fire ecologist for AMSET, Division of Ecosystem Science, Department of Environmental Science, Policy, and Management, University of California, Berkeley, Berkeley, CA.
vaillant@nature.berkeley.edu

² Fire ecologist for Nevada City, CA.

³ Assistant professor at UC Berkeley, Berkeley, CA.

The objective of this study is to determine how prescribed fire effects fuel loads, vegetation structure, and potential fire behavior and effects in eight National Forests in California. The null hypothesis investigated is that there will be no significant difference in vegetation structure, fuel load, fire behavior, and predicted tree mortality at each study site when comparing pre- and post-treatment characteristics. Information from this study could be used to assist in the development of forest management plans that use prescribed fire to reduce fire hazards.

Methods

Study Location

Nine project sites are located on eight National Forests: the Klamath (one on the eastern section, KNF E, and one on the western section, KNF W), Lassen (LNF), Los Padres (LPF), Modoc (MDF), Mendocino (MNF), Plumas (PNF), Shasta-Trinity (SHF) and Sierra (SNF) (fig. 1). LPF, MDF, MNF, and SNF are dominated by yellow pine [$>80\%$ of basal area is composed of ponderosa pine (*Pinus ponderosa* Laws) or Jeffrey pine (*Pinus jeffreyi* Grev.)] and KNF E, KNF W, PNF, and SHF are in mixed-conifer forests.

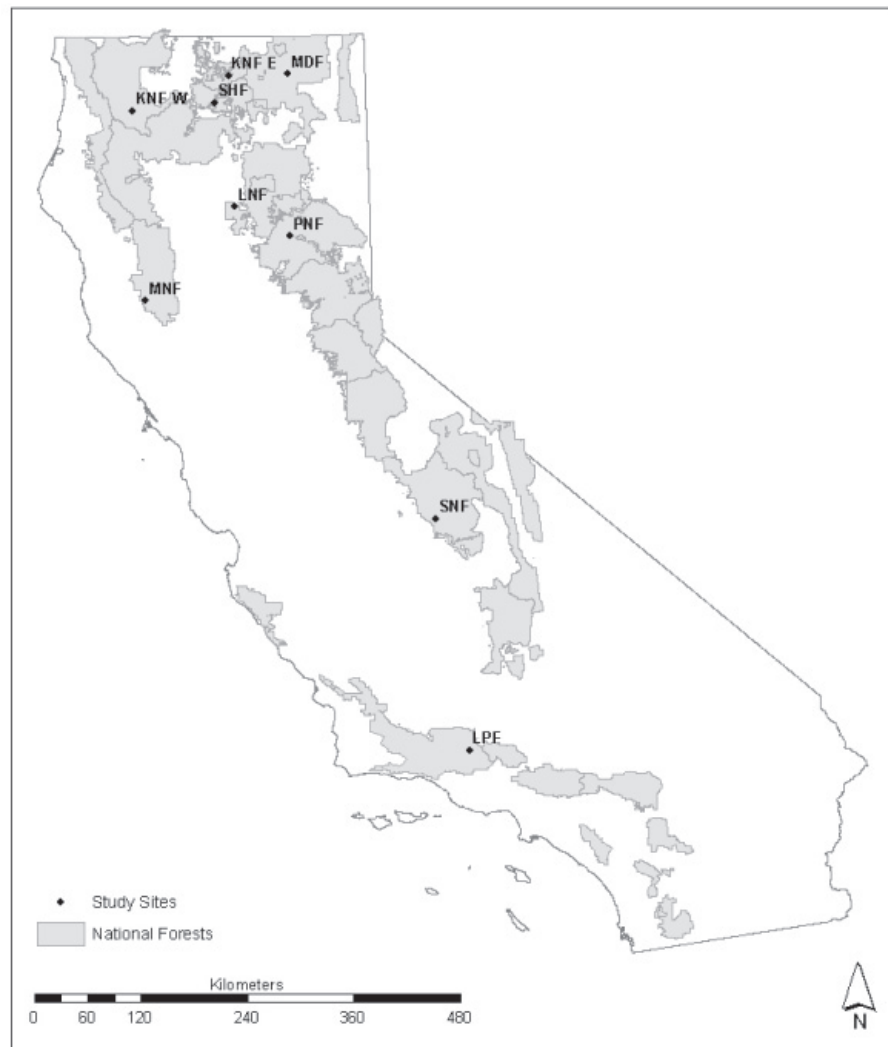


Figure 1—Location of study sites.

Climate in the study sites is Mediterranean with a summer drought period that extends into the fall. The majority of precipitation occurs during winter and spring. Tree species present include ponderosa pine, Jeffrey pine, sugar pine (*Pinus lambertiana* Dougl.), white fir (*Abies concolor* Gord. and Glend.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), incense-cedar (*Calocedrus decurrens* Torr.), western juniper (*Juniperus occidentalis* Hook.), California black oak (*Quercus kelloggii* Newb.), canyon live oak (*Quercus chrysolepis* Liebm.), and bigleaf maple (*Acer macrophyllum* Pursh).

The average elevation of the study sites ranges from approximately 1000 to 1600 m. Average slopes vary from three to 61 percent. Pre-treatment percent-cover of tree canopy, shrubs, and grasses varies between study locations.

Treatments

All of the study sites were treated with prescribed fire. The primary objectives of the prescribed burns were to reduce the potential for catastrophic stand replacing fire events and to reintroduce fire into the ecosystem. Each of the National Forests implemented their own prescribed fires. The prescribed fires occurred either in spring or fall depending on weather, available personnel, and funding, with the majority of prescribed fires taking place in the spring (six out of nine).

Vegetation Measurements

In each of the nine project sites, vegetation was measured using 0.2 ha randomly-placed, permanently-marked circular plots (26 total plots). Tree information was collected in two nested subplots; 0.1-ha for all trees greater than 15 cm diameter at breast height (d.b.h.), and 0.025 ha for trees 2.5 to 15 cm d.b.h. Tree measurements (species, d.b.h., height, height to live crown base (HTLCB), and tree crown position (dominant, codominant, intermediate or suppressed)) are recorded for live trees; for snags species, d.b.h., and total height was recorded. Canopy cover was measured every meter along two perpendicular 50 m transects using a Moosehorn sight tube (Gill and others 2000). Shrub measurements were also taken along the same transects in each of the plots to estimate percent shrub cover. An ocular estimate of percent cover by grasses was made along the shrub transect in a 1 m² frame every 10 m.

Ground and Surface Fuel Characteristics

Surface and ground fuels were measured with four transects in each of the plots using the line-intercept method (van Wagner 1968; Brown 1974). For each transect, one-hour (0 to 0.64 cm diameter) and 10-hour (0.64 to 2.54 cm diameter) fuels were sampled from 0 to 1.83 m, 100-hour fuels (2.54 to 7.62 cm diameter) from 0 to 3.66 m, and 1000-hour fuels (diameter >7.62 cm) from 0 to 15.24 m. Species, diameter, and decay status (rotten or sound) were recorded for all 1000-hour fuels. Litter, duff, and fuel bed depth (cm) measurements were taken every 1.52 m totaling 10 per transect. Surface and ground fuel loads were calculated using arithmetically-weighted coefficients specific to the California tree species based on the average basal area fraction of the individual sites (van Wagtendonk and others 1998; Stephens and Moghaddas 2005a).

Fire Modeling

Fire behavior and effects were modeled under upper 80th, 90th, and 97.5th percentile fire weather conditions. Eightieth, 90th, and 97.5th percentile fire weather represent moderate, high, and extreme fire weather, respectively. Percentile weather was computed using Fire Family Plus (Main and others 1990). Forty-three years (1961 to 2004) of weather data from the most representative Remote Automated Weather Station (RAWS) for each site (NFAM 2004) were analyzed to determine percentile weather conditions.

Fuels Management Analyst (FMA) was used to model fire behavior and effects (rate of spread, flame length, fireline intensity, crowning index, torching index, and tree mortality) (Carlton 2005). Fire behavior predictions were made for stand and fuel structures before and after prescribed burning. A surface fuel model was assigned to each sampling plot based on stand structure, shrub cover, grass cover, and fuel loads (Scott and Burgan 2005).

Data Analysis

Paired t-tests were used to determine if significant differences ($p < 0.1$) existed in vegetation (trees ha⁻¹, basal area ha⁻¹, tree height, HTLCB, canopy cover, crown bulk density (CBD)) and fuel loads (litter, duff, 1-hr, 10-hr, 100-hr, 1000-hr sound, 1000-hr rotten, total fuel load (1 to 1000-hr, litter and duff), and fuel depth) for each site pre- and post-prescribed fire (Zar 1999). The choice of $p < 0.1$ was made due to high natural variation found between plots in each study site. The number of sample plots varied by site location due to the ability of the individual National Forests to burn the proposed units and because some prescribed fires did not burn the entire intended area.

Results

Forest Structure

The inventory plots in the nine study locations included 860 live trees greater than 2.5 cm d.b.h. pre-treatment and 801 post-treatment. No significant differences were found for any of the measured variables (basal area, trees ha⁻¹, d.b.h., tree height, HTLCB, canopy cover, CBD) at KNF W, MDF, SHF or SNF (table 1). At LNF, LPF, MNF and PNF some but not all of the variables were significantly different (table 1). All variables were significantly different at KNF E except HTLCB.

Fuels Characteristics

A total of 104 fuel transects were analyzed over the nine project sites to characterize surface and ground fuels pre- and post-prescribed burning. All locations had a significant difference post-treatment in at least one of the fuels parameters (table 2). All of the locations except PNF experienced a significant reduction in litter loads. Total fuel load was reduced at all sites; however, the difference was only significant at MNF and LPF.

Potential Fire Behavior

Rate of spread (ROS) increased for all sites with increasing percentile weather (table 3). Post-treatment ROS either decreased or experienced no change when compared to pre-treatment. Flame length (FL) increased with

Table 1—Average pre- and post-treatment vegetation structure for all trees greater than 2.5 cm d.b.h. by site location for nine stands in eight Californian National Forests.

Site	Basal area (m ² ha ⁻¹)		Trees (ha ⁻¹)		DBH (cm)		Tree height (m)		HTLCB (m)		Canopy cover (percent)		CBD (kg m ⁻³)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
KNF E	37.0 ^a	36.0 ^a	706.7 ^a	533.3 ^a	27.2 ^a	29.6 ^a	14.4 ^a	15.6 ^a	4.9	4.6	43.2 ^a	35.3 ^a	0.094 ^a	0.091 ^a
KNF W	48.2	42.6	585.0	420.0	33.7	34.5	15.0	17.1	3.4	8.9	76.3	70.6	0.054	0.050
LNF	51.9	48.8	490.0 ^a	405.0 ^a	34.7	36.2	21.0	21.4	8.9	9.4	96.6	93.1	0.046	0.044
LPF	28.1	27.3	600.0	306.7	27.3	37.1	14.3	13.3	3.6	3.2	24.0 ^a	19.8 ^a	0.049 ^a	0.044 ^a
MDF	26.9	24.3	313.3	263.3	33.3	34.1	14.3	15.1	3.8	4.8	29.4	30.2	0.057	0.050
MNF	27.3	27.2	520.0	516.0	27.3	26.6	14.0	14.0	4.2	4.2	69.0 ^a	50.7 ^a	0.090	0.089
PNF	38.1	35.9	423.3	360.0	33.9	35.3	19.3 ^a	21.0 ^a	7.8 ^a	11.3 ^a	64.7	62.1	0.069	0.067
SHF	34.4	33.8	163.3	120.0	52.5	58.6	27.9	31.4	10.4	11.7	30.5	27.6	0.034	0.033
SNF	40.7	40.8	525.0	525.0	36.2	36.2	19.1	19.1	7.1	7.1	51.0	44.2	0.074	0.071

HTLCB= height to live crown base, CBD= crown bulk density, ^a=significantly different pre- versus post-treatment.**Table 2**—Average fuel loads (metric t ha⁻¹) pre- and post-treatment by site location.

Site	Duff		Litter		1-hr		10-hr		100-hr		1000-hr sound		1000-hr rotten		1-1000-h plus litter, duff		Fuel depth (cm)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
KNF E	21.4	2.2	11.1 ^a	4.4 ^a	1.5	0.9	2.7	1.3	2.8	2.5	3.5	6.5	39.7	0.0	82.7	17.8	28.2 ^a	7.7 ^a
KNF W	33.2	7.4	18.5 ^a	3.0 ^a	1.4	0.3	6.1	1.4	5.9	1.3	9.7	6.9	61.4	33.7	136.0	53.9	25.6	12.3
LNF	17.0	9.2	18.9 ^a	3.5 ^a	2.1	0.6	7.7	3.8	4.5	2.7	7.4	0.8	7.4	29.8	65.1	50.3	14.7	11.5
LPF	22.3 ^a	10.0 ^a	4.4 ^a	1.7 ^a	0.6	0.2	1.0	0.8	2.8	4.1	0.0	4.6	13.2	0.0	44.3 ^a	21.3 ^a	9.7	3.4
MDF	13.6	5.2	5.6 ^a	3.8 ^a	0.5 ^a	0.2 ^a	1.2	0.9	1.7 ^a	2.8 ^a	1.2	0.0	12.0	3.6	35.6	16.5	7.9	3.5
MNF	16.7	14.8	12.9 ^a	3.0 ^a	0.3	0.4	2.5	1.6	3.6	4.8	2.7	7.3	64.7 ^a	12.2 ^a	103.5 ^a	44.1 ^a	67.0 ^a	8.3 ^a
PNF	22.5	9.0	4.3	10.0	1.3	0.6	2.0	2.1	5.1	3.9	13.8	0.2	25.2	15.3	74.2 ^a	41.0 ^a	16.2 ^a	10.3 ^a
SHF	28.9 ^a	6.9 ^a	5.4 ^a	1.9 ^a	0.9 ^a	0.2 ^a	3.4 ^a	1.0 ^a	7.6	3.1	0.4 ^a	9.5 ^a	17.6	7.6	64.3	30.2	11.1 ^a	7.4 ^a
SNF	15.4	8.5	12.1 ^a	2.7 ^a	0.9	0.5	2.3	0.8	5.3	3.7	1.5	2.5	6.0	2.6	43.6	21.3	51.3	8.1

^a=significantly different pre- versus post-treatment.

Table 3—Average modeled fire behavior under 80th, 90th, and 97.5th percentile weather by site location.

Site	ROS			FL			FI			TI			CI		
	80 th	90 th	97.5 th	80 th	90 th	97.5 th	80 th	90 th	97.5 th	80 th	90 th	97.5 th	80 th	90 th	97.5 th
Pre	-- (m min ⁻¹) --			---- (m) ----			----- (kW m ⁻¹) -----			----- (km h ⁻¹) -----			----- (km h ⁻¹) -----		
KNF E	2.9	7.2	15.7	0.6	0.7	6.6	75.5	153	49286.6	152.8	119.5	109.7	41.5	37.2	33.2
KNF W	2.0	12.6	24.9	0.9	4.3	5.2	213.3	10476.3	16751.5	76.1	26.9	24.0	51.6	47.0	41.3
LNF	1.4	1.8	2.1	0.7	0.8	0.9	160.3	201.8	248.6	595.2	462.7	417.3	60.6	56.0	51.4
LPF	3.6	4.6	12.5	1.4	1.5	2.8	570.8	685.4	2950.5	35.3	26.2	23.2	75.9	67.0	60.6
MDF	1.2	1.6	2.9	0.8	1.0	1.2	185.5	245.9	379.3	135.9	104.5	88.5	73.1	68.4	60.8
MNF	6.4	8.3	16.0	3.2	3.7	7.1	5430.0	8500.2	44942.9	48.3	37.6	34.2	34.1	31.4	28.6
PNF	1.5	1.6	1.8	0.6	0.7	0.7	100.8	111.3	129.9	770.3	612.8	560.1	44.2	38.8	32.5
SHF	0.4	0.5	0.7	0.3	0.4	0.4	25.3	30.2	40.4	1894.2	1491.6	1401.0	80.6	75.1	70.4
SNF	1.8	4.5	5.4	0.9	1.4	1.5	22.9	578.4	685.9	212.2	140.1	117.7	45.6	29.8	24.7
Post															
KNF E	0.7	0.9	15.4	0.4	0.4	6.3	33.9	42.6	46828.1	434.7	347.0	321.2	42.8	38.4	34.2
KNF W	0.5	0.7	0.9	0.3	0.3	0.3	15.6	19.7	24.2	3023.2	2422.0	2218.5	58.0	53.0	46.8
LNF	0.5	0.7	0.8	0.3	0.3	0.3	15.9	19.9	21.9	2167.4	1766.4	1650.3	61.8	57.2	52.7
LPF	0.7	0.7	4.6	0.4	0.4	0.5	31.2	33.9	53.4	299.6	238.2	217.8	84.6	74.8	67.8
MDF	0.4	0.5	0.7	0.2	0.3	0.3	12.1	15.9	24.2	619.0	521.8	466.9	85.6	85.9	71.2
MNF	2.4	2.6	3.9	1.2	1.2	1.5	408.4	451.3	659.7	104.7	83.2	76.2	34.3	31.6	28.8
PNF	1.5	1.7	2.0	0.6	0.7	0.7	94.4	107.2	125.4	981.9	782.0	715.1	51.2	45.1	38.1
SHF	0.4	0.5	0.6	0.2	0.3	0.3	12.1	14.5	19.7	2677.8	2134.9	2012.2	82.9	77.2	72.4
SNF	0.6	0.7	0.7	0.3	0.3	0.3	17.7	21.9	21.9	1299.2	1052.0	968.1	47.2	40.4	38.1

ROS—rate of spread; FL—flame length; FI—fireline intensity; TI—torching index; CI—crowning index.

respect to higher percentile fire weather pre-treatment except at PNF and SHF where no change occurred between the 90th and 97.5th percentiles (table 3). FL was shorter post-treatment as compared to pre-treatment in all locations except PNF where it did not change. Modeled fireline intensity (FI) increased as percentile weather increased both pre- and post-treatment for all site locations except SNF (table 3). FI decreased post-treatment as compared to pre-treatment for all site locations. Torching index (TI) decreased as percentile weather increased pre- and post-treatment (table 3). Crowning index (CI) decreased with increasing percentile weather except at MDF where it only increased between the 80th and 90th percentile. CI increased slightly post-treatment for all locations, following the decreasing trend with respect to increasing severity of fire weather.

Fire type (FT) remained 100 percent surface fire in the LNF, PNF, SHF, and SNF sites pre- and post-treatment for all weather scenarios (table 4). Prescribed fire changed predicted FT in the KNF E, KNF W, LPF, MDF, and MNF sites by either decreasing the likelihood of crown fire or decreasing the severity of crown fire. At 80th and 90th percentile fire weather conditions, all post-treatment sites experienced only surface fire.

Predicted Tree Mortality

Probability of mortality was modeled for four diameter classes (2.5 to 25, 25 to 51, 51 to 76, >76 cm d.b.h.) as well as for all trees at each study site pre- and post-treatment (table 5). For all sites, a higher percentage of trees was predicted to die prior to treatment than after treatment. A higher amount of

Table 4—Modeled fire type under 80th, 90th, and 97.5th percentile weather by site location.

Site	80 th	90 th	97.5 th
Pre			
KNF E	33%PCF,66%SF	33%PCF,66%SF	33%ACFWD, 66%SF
KNF W	33%PCF,66%SF	33%SF, 66%PCF	33%SF,33%PCF,33%ACFPD
LNF	100%SF	100%SF	100%SF
LPF	33%PCF,66%SF	33%PCF,66%SF	33%SF, 66%PCF
MDF	100%SF	100%SF	33%PCF, 66%SF
MNF	40%PCF, 60%SF	40%PCF, 60%SF	20%PCF, 20%ACFPD, 60%SF
PNF	100%SF	100%SF	100%SF
SHF	100%SF	100%SF	100%SF
SNF	100%SF	100%SF	100%SF
Post			
KNF E	100%SF	100%SF	33%ACFWD, 66%SF
KNF W	100%SF	100%SF	100%SF
LNF	100%SF	100%SF	100%SF
LPF	100%SF	100%SF	33%PCF, 66%SF
MDF	100%SF	100%SF	100%SF
MNF	100%SF	100%SF	100%SF
PNF	100%SF	100%SF	100%SF
SHF	100%SF	100%SF	100%SF
SNF	100%SF	100%SF	100%SF

SF=surface fire; PCF=passive crown fire; ACFWD=active crown fire wind driven; ACFPD=active crown fire plume dominated.

mortality was predicted in smaller diameter classes (2.5 to 25 cm and 25 to 51 cm d.b.h.) regardless of location, weather condition, or treatment status. An increase in mortality with respect to increasing predicted fire weather conditions occurred in most study sites prior to prescribed fire; the trend was not the same post-treatment (table 5).

Table 5—Average pre- and post-prescribed burn percent predicted mortality by diameter class and site location for three percentile weather conditions.

	DBH range (cm)	KNF E	KNF W	LNF	LPF	MDF	MNF	PNF	SHF	SNF
Pre										
80 th	2.5-25	62.7	90.6	56.1	99.4	86.0	95.4	64.3	65.5	58.7
	25-51	21.9	52.1	24.1	70.5	27.5	79.6	17.5	20.4	17.3
	51-76	6.9	8.0	7.3	6.0	8.4	•	6.4	5.2	4.9
	>76	•	4.6	2.0	2.8	•	•	2.0	3.6	2.0
	All	30.5	38.8	22.4	44.7	40.6	87.5	22.5	23.7	20.7
90 th	2.5-25	66.5	98.1	57.8	99.6	92.4	96.9	64.7	65.5	77.5
	25-51	26.7	84.1	25.0	79.6	32.6	85.7	17.5	20.4	28.8
	51-76	8.2	50.0	8.0	8.9	12.1	•	6.4	5.2	5.4
	>76	•	48.3	2.0	3.8	•	•	2.0	3.6	2.0
	All	33.8	70.1	23.2	48.0	45.7	91.3	22.6	23.7	28.4
97.5 th	2.5-25	69.5	99.1	59.2	99.6	97.8	99.2	66.0	65.5	83.8
	25-51	46.6	87.9	26.6	89.0	44.0	95.5	17.6	20.4	37.2
	51-76	35.6	64.0	9.3	39.4	20.6	•	6.4	5.2	6.5
	>76	•	58.6	2.0	5.5	•	•	2.0	3.6	2.0
	All	50.6	77.4	24.3	58.4	54.1	97.3	23.0	23.7	32.4
Post										
80 th	2.5-25	52.3	58.9	46.0	52.4	53.6	81.7	52.2	40.2	48.0
	25-51	21.1	23.1	23.2	22.5	17.2	58.8	17.8	18.6	13.9
	51-76	6.9	5.6	8.6	7.1	5.0	•	6.3	5.2	4.3
	>76	•	2.9	2.0	2.4	•	•	2.0	3.6	2.0
	All	26.8	22.6	19.9	18.3	25.2	70.2	19.6	16.9	17.1
90 th	2.5-25	52.3	58.9	46.0	52.4	53.6	85.7	52.2	40.2	48.0
	25-51	21.1	23.1	23.2	22.5	17.2	67.2	17.8	18.6	13.9
	51-76	6.9	5.6	8.6	7.1	5.0	•	6.3	5.2	4.3
	>76	•	2.9	2.0	2.4	•	•	2.0	3.6	2.0
	All	26.8	22.6	19.9	18.3	25.2	76.5	19.6	16.9	17.1
97.5 th	2.5-25	65.7	58.9	46.0	56.9	53.9	87.6	52.3	40.2	48.0
	25-51	46.7	23.1	23.2	31.0	17.9	78.0	17.8	18.6	13.9
	51-76	35.6	5.6	8.6	16.6	5.2	•	6.3	5.2	4.3
	>76	•	2.9	2.0	2.4	•	•	2.0	3.6	2.0
	All	49.3	22.6	19.9	18.8	25.7	82.8	19.6	16.9	17.1

• = no trees in this diameter class for this location.

Discussion

Topography, weather, and fuels all play a role in the hazard and severity of wildland fire. Altering the fuel load is the most feasible and important factor to decrease hazard and severity of wildland fire. The vertical and horizontal continuity of surface fuels (litter and downed woody debris), ladder fuels (shrubs and small trees), and/or canopy fuels (large trees) must be broken to reduce fire severity. Reduction in surface fuels can reduce FI, increasing HTLCB can reduce the risk of torching, and reduction in crown density can limit tree-to-tree spread of crown fires (Agee 2002; Hessberg and Agee 2003; Agee and Skinner 2005).

Many studies in ponderosa pine and mixed-conifer forests document the effectiveness of prescribed fire in reducing future fire severity (Weaver 1943; Biswell and others 1973; Kauffman and Martin 1989; van Wagtendonk 1996; Stephens 1998; Miller and Urban 2000; Pollet and Omi 2002; Finney and others 2005; Knapp and others 2005; Stephens and Moghaddas 2005a,b). Prescribed fire effectively reduces surface fuel loads as well as kills shrubs and small diameter trees which reduce ladder fuels. Understory burning can also raise the height to live crown base through scorching of lower branches. One unifying goal of the prescribed burns analyzed in this work was to reduce the risk of stand-replacing catastrophic fire.

Stand characteristics did not significantly change in four of the nine site locations after treatment. This is consistent with many of the studies mentioned above. However, KNF E did experience a significant change in basal area, trees ha^{-1} , d.b.h., tree height, canopy cover, and CBD post-prescribed fire. This may be partially due to a tree blowdown event between plot readings (Kit Jacoby, personal communication). In the rest of the sites there were few differences in stand structure pre- and post-treatment. TI and CI moderately increased at all sites post-treatment, which indicates the need for an increase in wind speed to initiate and maintain crown fire. Overall, the modeled outputs document a reduced percentage of crown fires post-treatment; five treatments had a component of passive crown fire pre-treatment and two post-treatment (table 4).

If the primary goal of the prescribed fire treatment is to reduce the potential of stand replacing catastrophic wildfires, then TI and CI might be of particular interest. CI only increased slightly for all sites post-treatment indicating that the prescribed fire treatments did not effect the overstory (CBD or tree canopy cover). Under the 80th percentile fire weather condition, the untreated sites are unlikely to initiate crown fire due to high TI (table 3). For the 90th and 97.5th percentile fire weather conditions, pre-treatment values of TI and CI make the KNF W, LPF, and MNF sites more vulnerable to active crown fire (table 3). The reduction in likelihood of crown fire is due to a combination of changes in stand structures and surface fuel loads. Crown fire is not solely linked to canopy characteristics; surface fuel loads also play a critical role in active crown fire initiation and spread. If surface fireline intensity exceeds the critical level needed to initiate an active crown fire, the canopy is likely to burn as long as high surface fuel loads are present.

Fuel bed depth was significantly reduced at the KNF E, MNF, PNF and SHF sites; however, fuel bed depth was reduced by at least 20 percent at the remaining five sites, but was not statistically significant. Total fuel loads (surface and ground) were reduced significantly at LPF, MNF and PNF. The relatively high consumption of ground and surface fuels is consistent with past studies (Kilgore and Sando 1975; Kauffman and Martin 1989; Stephens and Finney 2002; Knapp and others 2005). Prescribed fire without

crown thinning has been shown to greatly reduce fireline intensity relative to no treatment (van Wagtenonk 1996; Stephens 1998). A reduction in surface fuel loads generally results in decreased fire severity, ROS, FL, and FI. Altered stand structures also contributed to the increase of surface fires versus crown fires post-treatment. Smaller diameter trees killed by prescribed fire are initially standing dead fuel. Eventually these trees will fall and contribute to the surface fuel loads (Stephens 1998; Agee 2003), necessitating future prescribed fires to keep hazards low.

Predicted tree mortality was higher pre-treatment than post-treatment for all locations under low, moderate, and extreme fire weather. Probability of tree mortality is primarily based on percent crown scorched which is derived from crown ratio, species tree height, and tree diameter (Reinhardt and others 1997). Predicted tree mortality was greatest in the smallest diameter class (2.5 to 25 cm d.b.h.) and decreased with increasing diameter classes (table 5). Increases in percentile fire weather post-treatment did not increase the likelihood of overall tree mortality at five sites (KNF W, LNF, PNF, SHF, SNF), it only slightly increased tree mortality in two sites (LPF and MDF), and it greatly increased tree mortality in two sites (KNF E and MNF). Predicted mortality almost doubled for all diameters at KNF E between the 90th and 97.5th percentile conditions post-treatment where fire type also changed; however, mortality was still lower relative to pre-treatment conditions (tables 4 and 5).

If reduction of potential stand replacing fires is the primary goal of prescribed fire treatments, selection of treatment locations must consider the existing fire hazards. Four of the nine study sites examined here only experienced modeled surface fire in pre-treatment conditions, including extreme fire weather conditions (table 4). Post-treatment potential fire behavior (ROS, FL, FI) was reduced, but these stands were not at risk of crown fire before treatment. On the other hand, three of the nine sites were at an elevated risk of crown fire (low TI and CI) pre-treatment at 97.5th percentile weather conditions (table 3). For the sites that would experience only surface fire, treatment is not warranted based on the reduction of potential fire behavior and effects. Sites experiencing low TI and CI values may benefit from a mechanical treatment (such as thinning from below) prior to prescribed fire to further reduce the risk of active crown fire.

In addition to the reduced potential for stand replacing catastrophic wildland fires, reintroduction of fire into the ecosystem was a primary goal of these prescribed fire treatments. Seasonality of prescribed fire is important from an ecological and fuels consumption standpoint. Fire history data from the southern Cascades in California document that prehistoric fires occurred mostly during the dormant season (starting as early as August and ending in October) in both pine dominated and mixed conifer forests (Taylor 2000; Beaty and Taylor 2001). In mixed conifer forests of the north-central, south-central, and southern Sierra Nevada, fires occurred most frequently just before dormancy in latewood growth (Stephens and Collins 2004). If reintroducing ecological processes is an important goal of a prescribed burn, it would be best if the burns took place in a time consistent with the fire history records.

Managers must consider many facets when choosing a location for treatment. With the amount of land rated at high hazard in California it would be wise to target stands which would benefit the most from treatment. If reintroduction of fire into the ecosystem is the primary goal and fuel reduction the secondary goal, then choosing treatment locations could include both stands with high and low fire hazards. Unfortunately, there is no one size fits all for fuel treatments in California; managers must consider many factors when implementing a forest restoration plan.

References

- Agee, J. A. 2002. The fallacy of passive management: managing for fire safe forest reserves. *Conservation Biology in Practice* 3 (1): 18-25.
- Agee, J. A. 2003. Monitoring post fire tree mortality in mixed-conifer forest reserves of Crater Lake, OR. *Natural Areas Journal* 23: 114-120.
- Agee, J. K. and C. N. Skinner. 2005. Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211: 83-96.
- Beaty, R. M. and A. H. Taylor. 2001. Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, Southern Cascades, California, USA. *Journal of Biogeography* 28: 955-966.
- Biswell, H. H. 1959. Man and fire in ponderosa pine in the Sierra Nevada of California. *Sierra Club Bulletin* 44: 44-53.
- Biswell, H. H., H. R. Kallander, R., Komarek, R. J. Vogl, and H. Weaver. 1973. Ponderosa Fire Management. Tall Timbers Research Station Misc. Publication No. 2. Tallahassee, FL: Tall Timbers Research Station. FL. 49pp.
- Brown, J. K. 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep. INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.
- Brown, J. K. and S. F. Arno. 1991. The paradox of wildland fire. *Western Wildlands Spring*: 40-46.
- Carlton, D. 2005. Fuels Management Analyst Plus. In: Fire Program Solutions, LLC.
- Dodge, M. 1972. Forest fuel accumulation- a growing problem. *Science* 177: 139-142.
- Finney, M. A., C. W. McHugh, and I. C. Genfell. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. *Canadian Journal of Forest Research* 35: 1714-1722.
- Gill, S. J., G. S. Biging, and E. Murphy. 2000. Modeling tree crown radius and estimating canopy cover. *Forest Ecology and Management* 126: 405-416.
- Hessburg, P. F. and J. A. Agee. 2003. An environmental narrative of inland Northwest U.S. forests, 1800-2000. *Forest Ecology and Management* 178: 23-59.
- Kauffman, J. B. and R. E. Martin. 1989. Fire behavior, fuel consumption, and forest-floor changes following prescribed understory fires in Sierra Nevada mixed conifer forests. *Canadian Journal of Forest Research* 19: 455-462.
- Keyes, C. R. and K. L. O'Hara. 2002. Quantifying stand targets for silvicultural prevention of crown fires. *Western Journal of Applied Forestry* 17 (2): 101-109.
- Kilgore, B. M. and R. W. Sando. 1973. The ecological role of fire in Sierran conifer forests: it's application to national park management. *Journal of Quaternary Research* 3: 496-513.
- Knapp, E. E., J. E. Keeley, E. A. Ballenger, and T. J. Brennan. 2005. Fuel reduction and coarse woody debris dynamics with early and late season prescribed fire in a Sierra Nevada mixed conifer forest. *Forest Ecology and Management* 208: 383-397.
- Main, W. A., D. M. Paananen, and R. E. Burgan. 1990. Fire Family Plus. Gen. Tech. Rep. NC-138. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station, St. Paul, MN. 35 p.
- Miller, C. and D. L. Urban. 2000. Modeling the effects of fire management alternatives on Sierra Nevada mixed-conifer forests. *Ecological Applications* 10 (1): 85-94.
- NFAM, 2004. National Fire and Aviation Management Web Applications. <http://famweb.nwcg.gov/weatherfirecd/california.htm>.

- Piñol, J., K. Beven, and D. X. Viegas. 2005. Modeling the effect of fire-exclusion and prescribed fire on wildfire size in Mediterranean ecosystems. *Ecological Modeling* 183: 397-409.
- Pollet, J. and P. N. Omi. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire* 11: 1-10.
- Reinhardt, E. D., R. E. Keane, and J. K. Brown. 1997. First order Fire Effects Model: FOFEM 4.0, User's Guide. Gen. Tech. Rep. INT-344. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 65 p.
- Scott, J. H. and R. E. Burgan. 2005. Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p.
- Stephens, S. L. 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in the Sierra Nevada mixed-conifer forests. *Forest Ecology and Management* 105: 21-35.
- Stephens, S. L. 2005. Forest fire causes and extent on United States Forest Service lands. *International Journal of Wildland Fire* 14: 213-222.
- Stephens, S. L. and M. A. Finney. 2002. Prescribed fire mortality of Sierra Nevada mixed conifer tree species: effect of crown damage and forest floor combustion. *Forest Ecology and Management* 162: 261-271.
- Stephens, S. L., and B. M. Collins. 2004. Fire regimes of mixed conifer forests in the north-central Sierra Nevada at multiple spatial scales. *Northwest Science* 78 (1): 12-23.
- Stephens, S. L. and J. J. Moghaddas. 2005a. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. *Forest Ecology and Management* 215: 21-26.
- Stephens, S. L. and J. J. Moghaddas. 2005b. Silvicultural and reserve impacts on potential fire behavior and forest conservation: twenty-five years of experience from Sierra Nevada mixed conifer forests. *Biological Conservation* 125: 369-379.
- Taylor, A. H. 2000. Fire regimes and forest change in mid and upper montane forests of the southern Cascades, Lassen Volcanic National Park, California, U.S.A. *Journal of Biogeography* 27: 87-104.
- van Wagner, C. E. 1968. The line intercept method in forest fuel sampling. *Forest Science* 14: 20-26.
- van Wagner, C. E. 1977. Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* 7: 23-34.
- van Wagtenonk, J. W. 1996. Use of a deterministic fire growth model to test fuel treatments. In: *Sierra Nevada Ecosystems Project: Final Report to Congress, vol. II. Assessments and Scientific Basis for Management Options*. University of California, Davis. Centers for Water and Wildland Resources: 1155-1165.
- van Wagtenonk, J. W. J. W. Benedict, and W. M. Sydoriak. 1998. Fuel bed characteristics of Sierra Nevada conifers. *Western Journal of Applied Forestry* 13: 1145-1157.
- Weaver, H. 1943. Fire as an ecological and silvicultural factor in the ponderosa-pine region of the Pacific slope. *Journal of Forestry* 41: 7-15.
- Zar, J.H. 1999. *Biostatistical Analysis*. Upper Saddle River, NJ: Prentice-Hall. 663 p.

Changes in Downed Wood and Forest Structure After Prescribed Fire in Ponderosa Pine Forests

Victoria Saab¹, Lisa Bate², John Lehmkuhl³, Brett Dickson⁴, Scott Story⁵, Stephanie Jentsch⁶, and William Block⁷

Abstract—Most prescribed fire plans focus on reducing wildfire hazards with little consideration given to effects on wildlife populations and their habitats. To evaluate effectiveness of prescribed burning in reducing fuels and to assess effects of fuels reduction on wildlife, we began a large-scale study known as the Birds and Burns Network in 2002. In this paper we analyze changes in downed wood and forest structure (trees and snags) measured within one year after prescribed fire treatments that were completed in ponderosa pine (*Pinus ponderosa*) forests in Arizona and New Mexico (Southwest region), and Idaho and Washington (Northwest region). Apparent reductions in downed wood and trees were observed in both regions. However, statistically significant reductions of downed wood were found primarily in the Northwest ($p < 0.001$), whereas significant reductions of trees were reported only for the Southwest ($p = 0.03$). No significant post-treatment changes were detected in snag densities, although we observed a pattern of non-significant increases in all size classes. Additional fire treatments are likely needed to meet fuels reduction goals. Results of this study are intended to assist managers with developing scientifically sound and legally defensible prescribed fire projects that will reduce fuels and concurrently enhance wildlife habitat.

Introduction

Fire regimes of lower elevation forests, particularly ponderosa pine (*Pinus ponderosa*) of the Interior Western United States, have been altered since Euro-American settlement (Agee 1993; Schoennagel and others 2004). Alterations in fire regimes and subsequent changes in forest structure and composition stem primarily from fire suppression, logging, and livestock grazing (Allen and others 2002; Schoennagel and others 2004; Veblen 2000). After decades of fire suppression, elevated fuel loads in many ponderosa pine forests have increased the likelihood of unusually large and severe fires (Arno and Brown 1991; Covington and Moore 1994), and the area burned annually has increased (Grissino-Mayer and Swetnam 2000; Keane and others 2002).

In an effort to restore ponderosa pine forest ecosystems, land managers have increasingly relied on prescribed burning (Horton and Mannan 1998; Arno 2000; Machmer 2002; Carey and Schumann 2003). Most prescribed fire plans focus on reducing the intensity of wildfire, with little consideration given to effects on wildlife populations and their habitats. Strategies for fire management should not only reduce fire risk but also maintain habitat for wildlife and other components of biodiversity (Saab and others 2005).

Ponderosa pine trees, snags and downed wood are among the most valuable habitat components for wildlife species in western North American forests (Balda 1975; Bull and others 1997; Hall and others 1997; Szaro and others

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

¹ Research Biologist with the US Forest Service, Rocky Mountain Research Station, MSU Campus Bozeman, MT. vsaab@fs.fed.us

² Research Wildlife Biologist contracting with the US Forest Service, Rocky Mountain and the Pacific Northwest Research Stations, Kalispell, MT.

³ Research Wildlife Biologist with the US Forest Service, Pacific Northwest Research Station, Wenatchee Forestry Sciences Lab, Wenatchee, WA.

⁴ PhD Graduate Research Assistant at the Noon Lab of Conservation and Landscape Ecology, Department of Fishery and Wildlife Biology, College of Natural Resources, Colorado State University, Fort Collins, CO.

⁵ Masters Graduate Research Assistant in the Ecology Department, Montana State University, Bozeman, MT.

⁶ Masters degree in Wildlife and Fisheries Science at the University of Arizona, Department of Natural Resources, University of Arizona, Biological Sciences, Tucson, AZ.

⁷ Project Leader/Supervisory Research Wildlife Biologist for the Rocky Mountain Station, Southwest Forest Science Complex, Flagstaff, AZ.

1988). Large-diameter ponderosa pine snags, trees with decay, and downed logs are relatively easy to excavate by woodpeckers and provide roosting, nesting, and foraging habitat for a variety of wildlife (Bull and others 1997; Hall and others 1997; Szaro and others 1988; Scott 1979).

Many cavity-nesting birds depend on fire-disturbed landscapes for breeding, dispersal, and other portions of their life history (Saab and others 2004). Several cavity nesters are designated by state, federal, and provincial governments as species at-risk because they are responsive to fire and timber management activities. Stand-replacement fires in conifer forests are particularly important to breeding and wintering cavity-nesting birds (Blackford 1955; Raphael and White 1984; Saab and Dudley 1998; Kriesel and Stein 1999; Hannon and Drapeau 2005). Little is known, however, about bird population responses to prescribed fire, particularly in the Intermountain region (Bock and Block 2005; Saab and others 2005). In 2002, we began a regional study to evaluate effectiveness of prescribed fire in reducing fuels and to assess the effects of fuels reduction on habitats and populations of birds in ponderosa pine forests throughout the Interior West. Our study is known as the Birds and Burns Network (BBN) (see web page <http://www.rmrs.nau.edu/lab/4251/birdsnburns/>), with study areas located in seven states encompassing much of the range of ponderosa pine in the United States (Arizona, Colorado, Idaho, Montana, New Mexico, Oregon, and Washington). As of 2005, study areas in Arizona and New Mexico (Southwest region; SW), and Idaho and Washington (Northwest region; NW) have received prescribed fire treatments.

In this paper, our objective was to evaluate the magnitude of change in the quantities of downed wood, dead stems (hereafter termed snags), and live stems (hereafter termed trees) measured within one year after prescribed fire treatments. Based on previous studies (Horton and Mannan 1988; Machmer 2002; McHugh and Kolb 2003; Raymond and Peterson 2005), we hypothesized that downed wood of all sizes, large snags (≥ 9 inch diameter breast height [d.b.h.]), and smaller trees (< 9 inch d.b.h.) would be reduced as a result of prescribed burning, whereas we expected smaller snags (< 9 inch d.b.h.) to increase after fire treatments. Results of this study are intended to help managers develop scientifically sound and legally defensible prescribed fire projects that will reduce fuels and concurrently maintain and enhance wildlife habitat.

Study Area and Methods

Study areas were located in forests dominated by ponderosa pine, where prescribed fire treatments were implemented by the USDA National Forests. On each study area, a single treatment unit ranged in size from 500 to 1000 acres and was paired with an unburned control unit of equivalent area. As of 2005, prescribed fire treatments were completed at seven study units in four states and data from these units were used in the analyses presented in this paper. General objectives of these “low-intensity” fire treatments included fuels reduction, fire threat mitigation, and forest restoration.

Pre-treatment data were collected during the summers of 2002 and 2003. Four units were treated with fire in the SW on USDA National Forests (NF); two units during fall 2003 in Arizona (Apache-Sitgreaves and Coconino NFs), and two units that were initiated in fall 2003 and completed during spring 2004 in New Mexico and Arizona (Gila and Kaibab NFs, respectively). Three units were treated in the NW during spring 2004, one unit in Idaho

(Payette NF) and two units in Washington (Okanogan and Wenatchee NFs). Post-treatment data were collected one growing season after fire treatments during the summers of 2004 or 2005.

Overstory vegetation (trees ≥ 9 inches d.b.h.) on all units in both regions was dominated by ponderosa pine. For trees ≥ 20 inch d.b.h. or larger, ponderosa pine was also the dominant tree species for all locations except for the Gila NF, where alligatorbark juniper (*Juniperus deppeana*) had higher densities.

In Arizona, common understory vegetation included green rabbitbrush (*Chrysothamnus viscidiflorus*) and Fendler rose (*Rosa woodsii*), whereas gambel oak dominated the understory in New Mexico. Arizona fescue (*Festuca arizonica*) and blue gramma (*Bouteloua gracilis*) were the most common grass species throughout the SW. Elevations in the SW region ranged from 6800 feet on the Coconino NF to nearly 8200 feet on the Gila NF.

The understory vegetation in the NW was comprised of various species, including snowberry (*Symphoricarpos albus*), spirea (*Spirea* spp.), serviceberry (*Amelanchier alnifolia*), and chokecherry (*Prunus* spp.). Bluebunch wheatgrass (*Pseudoroegneria spicata*) and Idaho Fescue (*Festuca idahoensis*) were the common grass species. Elevations ranged from 2200 feet in Washington to 6500 feet in Idaho.

Within each unit we established 20 to 40 permanently marked 1-acre random plots to measure fuel and vegetative characteristics. All plots centers were at least 820 feet apart (Dudley and Saab 2003). To determine the effects of prescribed fire on downed wood, snags, and trees, we measured these forest components at each plot before (pre) and after (post) prescribed fire. We considered the difference in pre and post values by plot to be a measure of the treatment effect size.

Measurements were nested within the 1-acre plot configured as two 66 x 326 feet rectangles that crossed in the center (that is, a rectangular cross plot). Tree and snag measurements followed methods outlined by Bate and others (1999). Snags ≥ 9 inches d.b.h. were counted within 33 feet of the centerline in the rectangular cross plot. Trees ≥ 9 inches d.b.h. were counted within 16.5 feet of the centerline in the SW and within 9.8 feet in the NW. Plot widths for trees and snags were based on power analyses of pilot data from each location to maximize efficiency of data collection (Bate and others 1999). For trees and snags < 9 inches, we counted within 6.6 feet of the centerline in the SW and within 3.3 feet in the NW.

In this paper we present preliminary results for both snags and trees in four categories: (1) < 3 inch; (2) ≥ 3 to 9 inch; (3) ≥ 9 inch; and (4) total density of all stems (snags or trees). Snags and trees in the ≥ 9 inch d.b.h. category were of special interest to us because they commonly represent the smallest size class that woodpeckers use for nesting (for example, Saab and others 2004) and the smallest sized trees harvested for timber values (USDA 1996).

We measured the weight (tons per acre) of downed wood following Brown's (1974) protocol. Downed wood is defined as the "... dead twigs, branches, stems, and boles of trees and brush that have fallen and lie on or above the ground" (Brown 1974, page 1). Downed wood pieces less than 1 inch diameter (1- and 10-hour fuels) were sampled along 41 feet of transect in two directions (north and south) from the plot center. Material in the ≥ 1 to 3 inch size class (100-hour fuels) was measured in the same two directions but along twice the length (82 feet). For coarse wood ≥ 3 inches (≥ 1000 -hour fuels), we recorded the intersection diameter of each woody piece along 164 feet in each of the four cardinal directions originating from the plot center (total of 656 feet sampled). Downed wood pieces ≥ 3 inch were classified as either sound or rotten and we used the specific gravities provided by Brown (1974)

to obtain a weight estimate for each condition class. That is, we used 24.96 lbs/ft³ and 18.72 lbs/ft³ for sound and rotten wood, respectively, relative to the density of water (62.4 lbs/ft³) (Brown and See 1981). Here, we present results for downed wood in four size categories: (1) < 3 inch; (2) ≥ 3 inch; (3) ≥ 9 inch; and (4) total weight of all downed wood. Weights calculated for the ≥ 9 inch category were based on the large-end diameter (LED), whereas weights of other size classes were based on the intersect diameter.

We calculated a response to the prescribed fire as an “effect size” on each plot, which represented the change in fuels attributable to the prescribed fire. The effect size was measured by subtracting pre-fire fuel quantities from post-fire fuel quantities. We then computed least-squares means (PROC MIXED SAS Institute 2003) to test whether the effect size was significantly different from zero for weight of downed wood, snag densities, and tree densities. We accepted $p \leq 0.05$ as the observed probability level for Type I error in hypothesis tests. We used a nested analysis with plots nested within units, and units nested within regions. Results are reported for the mean effect size of stems per acre (± 1 standard error [SE]) and tons per acre (± 1 SE) at the regional level. A likelihood ratio test was computed to compare a model with a pooled estimate of variance across regions to a model with a separate variance estimate for each region. Generally, the model with separate variance estimates had significantly better goodness-of-fit and was used for the least-squares means analysis. Pooled variance results are reported only for trees ≥ 9 inch d.b.h. and for total trees.

Results

Weight of downed wood in all size classes decreased after prescribed fire treatments (Table 1), however most of the statistically significant differences were measured in the NW (Table 2). Downed wood was reduced by 25 to 43 percent in the SW and by 29 to 58 percent in the NW. Total weight of downed wood was reduced by nearly half in the NW region, where most of the downed material was comprised of large logs ≥ 9 inches LED (Table 1). In contrast to the NW, pre-fire weight of downed wood in the SW region was composed almost exclusively of small diameter material < 9 inches LED (Table 1).

Our hypothesis about reductions of small diameter (< 9 inches d.b.h.) trees (seedlings, saplings, and poles) was generally supported by the data; however, trees of all diameter classes in the SW region also decreased significantly after fire treatments (Table 2). Trees were reduced by 19 to 74 percent in the SW and 0 to 39 percent in the NW (Table 1). Stems in the smallest size class (< 3 inches) contributed the most to changes in tree densities, whereas large tree (≥ 9 inches) densities changed the least.

We hypothesized that snags of the smaller size classes (< 9 inches d.b.h.) would increase and that large snags (≥ 9 inches d.b.h.) would decrease after fire treatments. Our results indicated no significant post-treatment changes in snag densities (Table 2), although we observed a pattern of non-significant increases in all size classes (Table 1). Increases in snags ranged from 30 to 72 percent in the SW and 29 to 229 percent in the NW. Large snags (≥ 9 inches d.b.h.) contributed to the greatest changes in dead stems in the SW, whereas smaller diameter stems (≥ 3 – 9 inches d.b.h.) contributed most to snag changes in the NW.

Table 1—Means, standard errors (SE), and percent change for downed wood (DW; mean tons per acre), and trees, and snags (mean stems per acre) measured pre- and post-fire treatment by region (Southwest [SW] and Northwest [NW]) in the Birds and Burns Network during 2002-2005. Downed wood was measured at large end diameter (LED) and stems were measured at diameter breast height (d.b.h.).

		SW [n = 134]			NW [n = 60]		
Size class		Pre-fire mean	Post-fire mean	Percent change	Pre-fire mean	Post-fire mean	Percent change
(inches)		----- (SE) -----			----- (SE) -----		
DW (tons/ac)	< 3	2.0 (0.2)	1.5 (0.1)	-25	1.8 (0.2)	1.3 (0.1)	-27.8
	≥ 3	2.3 (0.2)	1.3 (0.1)	-43.5	7.6 (0.8)	3.8 (0.5)	-50
	≥ 9	0.7 (0.1)	0.4 (0.1)	-42.9	6.3 (0.8)	2.6 (0.4)	-58.7
	Total	4.3 (0.3)	2.8 (0.2)	-34.9	9.4 (0.9)	5.1 (0.5)	-46
Trees (stems/ac)	< 3	256 (26.5)	66.3 (12.6)	-74.1	234 (29.4)	144 (26.6)	-38.5
	≥ 3 to 9	124 (9.5)	72.6 (8.4)	-41.5	191 (23.6)	133 (17.1)	-30.4
	≥ 9	52.2 (2.5)	42.2 (2.9)	-19.2	45.5 (2.4)	48.1 (2.9)	+0.57
	Total	432 (33.2)	181 (18.2)	-58.1	470 (46.8)	324 (36.2)	-31.1
Snags (stems/ac)	< 3	28.6 (3.9)	44.6 (5.6)	+55.9	62.2 (10.2)	110 (16.7)	+76.8
	≥ 3 to 9	15 (2)	19.5 (2.4)	+30	12.7 (2.1)	41.8 (7.9)	+229
	≥ 9	2.5 (0.3)	4.3 (0.7)	+72	2.8 (0.4)	3.6 (0.5)	+28.6
	Total	46 (5.4)	68.4 (7.5)	+48.7	77.6 (11.5)	156 (23.5)	+101

Table 2—Results of least-square means analysis to test for statistical differences from zero, or no change in the quantity of downed wood (DW; tons per acre), trees (stems per acre), and snags (stems per acre) measured pre- and post-prescribed fire in western ponderosa pine forests. Mean estimate of the effect size, standard error of the estimate (SE), t-value, p-value, and sample size [n] are reported for each size class by region (Southwest [SW] and Northwest [NW]) in the Birds and Burns Network during 2002-2005.

		SW [n = 134]				NW [n = 60]			
Size class		Estimate (effect size)	SE	t-value	p-value	Estimate (effect size)	SE	t-value	p-value
(inches)									
DW (Δ in tons/ac)	< 3	-0.49	0.32	-1.53	0.19	-0.46	0.43	-1.06	0.34
	≥ 3	-1.15	0.43	-2.68	0.04	-3.9	0.58	-6.71	0.001
	≥ 9	-0.4	0.18	-2.11	0.09	-3.7	0.54	-6.83	0.001
	Total	-1.66	0.73	-2.28	0.07	-4.3	0.36	-11.97	<0.001
Trees (Δ in stems/ac)	< 3	-212.6	28.6	-2.7	0.04	-107.1	47.5	-2.26	0.07
	≥ 3 to 9	-60.9	29.5	-2.07	0.09	-61.1	35.2	-1.74	0.14
	≥ 9	-13.3	8.06	-1.65	0.16	2.9	9.38	0.31	0.77
	Total	-287.1	99.9	-2.37	0.03	-165.2	117.3	-1.41	0.22
Snags (Δ in stems/ac)	< 3	19.4	13.7	1.42	0.21	47.9	19.5	2.45	0.06
	≥ 3 to 9	5.4	4.2	1.29	0.25	29.2	17.6	1.65	0.16
	≥ 9	1.86	1.06	1.75	0.14	0.79	0.55	1.43	0.21
	Total	26.6	14.8	1.80	0.13	77.9	37.2	2.09	0.09

Discussion

Decreases in downed wood and trees supported our hypotheses regarding changes in these forest components after prescribed fire treatments. While we expected only the smaller size classes of snags (< 9 inch d.b.h.) to increase after prescribed fire, we observed a pattern of non-significant increases in large snag (≥ 9 inch d.b.h.) densities as well. Apparently, prescribed fire treatments were severe enough to kill trees of all size classes, particularly in the SW where this result was statistically significant.

Nearly half of large downed wood (≥ 9 inch LED) was consumed by prescribed fire in both regions. Drought conditions, followed by low wood moistures prior to fire treatments, may have contributed to the large loss of downed wood. When moisture contents are less than 15 percent, fire generally consumes about half of large downed woody materials (Brown and others 1985). Efforts to retain these large structures may require seasonal adjustments for burning times when moisture contents are higher and fire severity effects are lower (Thies and others 2005). Maintenance of large, downed wood is important ecologically because these structures provide foraging habitat, thermal cover, and concealment for many sensitive wildlife taxa (Bull and others 1997; Szaro and others 1988), although logs may have been a limited resource in low-severity fire regimes (Agee 2002).

Overall tree densities in the SW were significantly reduced after fire treatments. Although we observed a pattern of decreased tree densities in the NW, no statistical differences were detected in densities measured before and after prescribed fire. We think, however, that all observed changes in tree densities were important ecologically. For example, in both regions we observed the greatest reduction of tree densities in the smallest size class (< 3 inches d.b.h.), followed by reductions in the medium size class (≥ 3 to < 9 inch), with little change in large (≥ 9 inches d.b.h.) tree densities. Small diameter trees function as ladder fuels in dense stands by carrying flames into the crowns of mature trees, where the potential for larger tree mortality increases (Pollet and Omi 2002). Indeed, prescribed fire programs that remove small diameter trees can reduce the likelihood and cost of stand-replacing fires (Arno 1980; Fernandes and Botelho 2003; Pollet and Omi 2002).

We observed relatively little change in densities of large trees ≥ 9 inch d.b.h. This result was not surprising because the thick bark of ponderosa pine is fire-resistant, improving tree survival during low to moderate severity burns (Agee 1993). Historically, large-diameter ponderosa pines were harvested because of their high timber and fuelwood values (Agee 1993). These same trees are also among the most valuable for many wildlife species of conservation concern (Bull and others 1997; Lehmkuhl and others 2003; Saab and others 2004). Retention of large-diameter snags and decayed trees, particularly ponderosa pine, can provide vital nesting and roosting habitat for a variety of wildlife species (Bull and others 1997; Martin and Eadie 1999). For example, the sapwood of ponderosa pine is relatively thick compared to other conifers and exceptionally valuable for the excavation of nesting and roosting tree cavities (Bull and others 1997).

We observed apparent increases in snag densities, including the large diameter size class in both regions. While this pattern was not statistically significant, the result has implications for the creation of wildlife habitat. Maintenance and recruitment of larger diameter snags is particularly important because large snags have greater longevity and provide wildlife habitat for a longer period of time than smaller snags (Raphael and Morrison 1987; Everett and others 1999; Saab and others 2004). Additional tree mortality is expected two to three years after fire, because time allows for crown scorch and consumption to cause further tree death (McHugh and Kolb 2003).

In contrast to our results that suggest increased densities of large snags after fire, Horton and Mannan (1988) reported that large ponderosa pine snags were reduced by about 50 percent within the first year after a moderately-intense prescribed fire. Detrimental effects of prescribed fire on suitable nesting snags were also reported in ponderosa pine forests of Canada, where burning caused heavy scorching of large snags (Machmer 2002). Differences

in fire severity among studies likely contributed to the opposing results of snag changes after prescribed fire.

Several authors suggest protecting nest trees by removing combustible materials around their base prior to burning to reduce losses of suitable nest/roost snags (Horton and Mannan 1988; Machmer 2002; Tiedemann and others 2000). Specifically, Horton and Mannan (1988) recommend protecting large (>50 cm [20 inch] d.b.h.) snags and logs with moderate decay. Tiedemann and others (2000) recommended removing combustible material around snags > 30 cm (12 inch) d.b.h. These methods are labor intensive and cost prohibitive for large-scale prescribed fire programs, unless snag protection is required for Threatened and Endangered species. While prescribed fire consumed some wildlife snags, burning also recruited snags (Table 1). Direct effects of prescribed burning on wildlife should also be considered. For example, prescribed fires conducted during spring or early summer may cause direct mortality to nestlings and fledglings (Lyon and others 2000).

Smaller snag (< 9 inch d.b.h.) densities increased 30 to 60 percent in the SW and two to four times that amount in the NW region. While still standing, these dead trees contribute to increased risk of spot fires (Stephens and Moghaddas 2005). With time, these stems create ground fuels and increase the likelihood of higher fire intensities (Reinhardt and Ryan 1998). Such fuel accumulations can limit the effectiveness of prescribed fire programs to a relatively short period of time such as two to four years (Fernandes and Botelho 2003). Studies suggest that relatively frequent, natural fires are necessary to maintain ponderosa pine forests in a diverse landscape mosaic more common to historical conditions (Brown and Cook 2006; Fry and Stephens 2006) that existed just prior to European settlement. Similarly, prescribed fires also have the potential to mitigate the likelihood of severe crown fires (Fernandes and Botelho 2003; Finney and others 2005; Pollet and Omi 2002; Raymond and Peterson 2005), which were once rare but regular events in ponderosa pine forests (Shinneman and Baker 1998).

Few of our results were statistically significant at $p \leq 0.05$. Managers willing to take more acceptable risk can interpret our results as being more definitive by using a significance level of $p \leq 0.10$ (Zar 1999). Inherent differences in pre-treatment forest structure existed in our ponderosa pine forests, which possibly influenced fire behavior and resulted in high variability in the effectiveness of fuels reduction. The power to detect statistically significant changes is low without large numbers of replicates. However, long-term prescribed fire programs can still play an important role in reducing fire hazard potential (Fernandes and Botelho 2003), suggesting that our study areas may require multiple fire treatments to reach fuels reduction and restoration goals. In addition, wildland fire can also be used to effectively reduce fuels and to closely mimic past disturbance regimes in ponderosa pine forests (Baker and Ehle 2001).

In this paper we did not evaluate the influence of fire severity on changes in fuels and other vegetation after fire. In the future, we plan to incorporate fire severity data to help with understanding the influences of severity on vegetation mortality, and wildlife populations and their habitat (Saab and Powell 2005). Also, we recommend monitoring vegetation and wildlife populations for several years after prescribed burning because of changes in vegetation and wildlife responses with time since fire (Hannon and Drapeau 2005; McHugh and Kolb 2003; Reinhardt and Ryan 1998; Saab and others 2004). Severity information and monitoring for multiple years after fire will help in developing guidelines for prescribed fire projects that will reduce fuels and concurrently create wildlife habitat.

Acknowledgments

This study was funded by the Joint Fire Sciences Program, National Fire Plan, USDA Rocky Mountain Research Station, USDA Pacific Northwest Research Station, Intermountain Region of the USDA Forest Service, and the USDA Payette National Forest. We thank Craig Bienz and Robin Russell for thoughtful comments on the manuscript. Rudy King provided guidance on statistical analyses. We are grateful to the many field assistants who worked long, hot days to collect the field data.

References

- Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Washington, DC: Island Press: 493 p.
- Agee, J. K. 2002. Fire as a coarse filter for snags and logs. In: Shea, P. J.; Laudenslayer, Jr., W. F.; Valentine, B.; Weatherspoon, C. P.; Lisle, T. E., eds. Proceedings of the Symposium on The Ecology and Management of Dead Wood in Western Forests, Gen. Tech. Rep. PSW-GTR-181. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 359-368.
- Allen, C. D.; Savage, M.; Falk, D. A.; Suckling, K. F.; Swetnam, T. W.; Schulke, T.; Stacey, P. B.; Morgan, P.; Hoffman, M.; Klingel, J. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: A broad perspective. *Ecological Applications*. 12: 1418-1433.
- Arno, Stephen F. 2000. Fire in western forest ecosystems. In: Brown, J. K.; Smith, J. K., eds. *Wildland fire in ecosystems: effects of fire on flora*. Gen. Tech. Rep. RMRS-GTR-42-vol. 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 97-120.
- Arno, S. F.; Brown, J. K. 1991. Overcoming the paradox in managing wildland fire. *Western Wildlands*. 17: 40-46.
- Baker, W. L.; Ehle, D. 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. *Canadian Journal of Forest Research*. 31: 1205-1226.
- Balda, R.P. 1975. The relationship of secondary cavity nesters to snag densities in western coniferous forests. *Wildlife Habitat Technical Bulletin* 1. Albuquerque, NM: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 37 p.
- Bate, L. J.; Garton, E. O.; Wisdom, M. J. 1999. Estimating snag and large tree densities and distributions on a landscape for wildlife management. Gen. Tech. Rep. PNW-GTR-425. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 76 p.
- Blackford, J. L. 1955. Woodpecker concentration in burned forest. *Condor*. 57: 28-30.
- Bock, C. E.; Block, W. M. 2005. Fire and birds in the southwestern United States. *Studies in Avian Biology*. 30: 14-32.
- Brown, J. K. 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep. INT-GTR-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.
- Brown, J. K.; See, T. E. 1981. Downed dead wood fuel and biomass in the Northern Rocky Mountains. Gen. Tech. Rep. INT-GTR-117. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 48 p.

- Brown, J. K.; Marsden, M. A.; Ryan, K. C.; Reinhardt, E. D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the Northern Rocky Mountains. Gen. Tech. Rep. INT-GTR-337. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 23 p.
- Brown, P. M.; Cook, B. 2006. Early settlement forest structure in Black Hills ponderosa pine forests. *Forest Ecology and Management*. 223: 284–290.
- Bull, E. L.; Parks, C. G.; Torgersen, T. R. 1997. Trees and logs important to wildlife in the Interior Columbia River basin. Gen. Tech. Rep. PNW-GTR-391. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 55 p.
- Carey, H.; Schuman, M. 2003. Modifying wildfire behavior – the effectiveness of fuel treatments: the status of our knowledge. National Community Forestry Center, Southwest Region Working Paper 2. (<http://www.theforesttrust.org/images/swcenter/pdf/workingpaper2.pdf>)
- Covington, W. W.; Moore, M. M. 1994. Southwestern ponderosa forest structure: changes since Euro-American settlement. *Journal of Forestry*. 92: 39-47.
- Dudley, J.; Saab, V. 2003. A field protocol to monitor cavity-nesting birds. Res. Pap. RMRS-44. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 16 p.
- Everett, R.; Lehmkuhl, J.; Schellhaas, R.; Ohlson, P.; Keenum, D.; Reisterer, H.; Spurbeck, D. 1999. Snag dynamics in a chronosequence of 26 wildfires on the east slope of the Cascade Range in Washington state, USA. *International Journal of Wildland Fire*. 9: 223-234.
- Fernandes, P. M.; Botelho, H. S. 2003. A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of Wildland Fire*. 12: 117-128.
- Finney, M. A.; McHugh, C. W.; Grenfell, I. C. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. *Canadian Journal Forest Research*. 35: 1714-1722.
- Grissino-Mayer, H. D.; Swetnam, T. W. 2000. Century scale changes in fire regimes and climate in the Southwest. *The Holocene*. 10: 207-214.
- Hall, L. S.; Morrison, M. L.; Block, W. M. 1997. Songbird status and roles. In: Block, W. M.; Finch, D. M., eds. *Songbird ecology in Southwestern ponderosa pine forests: a literature review*. Gen. Tech. Rep. RM-GTR-292. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 69-88.
- Hannon, S.; Drapeau, P. 2005. Bird responses to burning and logging in the boreal forest of Canada. *Studies in Avian Biology*. 30: 97-115.
- Horton, S. P.; Mannan, W. R. 1988. Effects of prescribed fire on snags and cavity-nesting birds in southeastern Arizona pine forests. *Wildlife Society Bulletin*. 16: 37-44.
- Keane, R. E.; Ryan, K. C.; Veblen, T. T.; Allen, C. D.; Logan, J.; Hawkes, B. 2002. Cascading effects of fire exclusion in Rocky Mountain ecosystems: a literature review. Gen. Tech. Rep. RMRS-GTR-91. Fort Collins, CO: U.S. Department of Agriculture, Forest Service General Technical Report. Rocky Mountain Research Station.
- Kreisel, K. J.; Stein, S. J. 1999. Winter and summer bird use of burned and unburned coniferous forests. *Wilson Bulletin*. 111: 243-250.
- Lehmkuhl, J. F.; Everett, R. L.; Schellhaas, R.; Ohlson, P.; Keenum, D.; Riesterer, H.; Spurbeck, D. 2003. Cavities in snags along a wildfire chronosequence in eastern Washington. *Journal of Wildlife Management*. 67: 219-228.
- Lyon, L. J.; Telfer, E. S.; Schreiner, D. S. 2000. Direct effects of fire and animal responses In: Smith, J. K. ed. *Wildland fire in ecosystems: effects of fire on fauna*. Gen. Tech. Rep. RMRS-GTR-42-vol. 1. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 17-23.

- Machmer, M. 2002. Effects of ecosystem restoration treatments on cavity-nesting birds, their habitat, and their insectivorous prey in fire-maintained forests of southeastern British Columbia. In: Shea, P. J.; Laudenslayer, Jr., W. F.; Valentine, B.; Weatherspoon, C. P.; Lisle, T. E., eds. *Proceedings of the Symposium on The Ecology and Management of Dead Wood in Western Forests*, Gen. Tech. Rep. PSW-GTR-181. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 121-133.
- Martin, K.; Eadie, J. M. 1999. Nest webs: a community-wide approach to the management and conservation of cavity-nesting forest birds. *Forest Ecology and Management*. 115: 243-257.
- Peterson, D. L.; Johnson, M. C.; Agee, J. K.; Jain, T. B.; McKenzie, D.; Reinhardt, E. D. 2003. Fuels planning: Managing forest structure to reduce fire hazard. In: *Proceedings of the Second International Wildland Fire Ecology and Fire Management Congress*, Orlando, FL. 10 p.
- Pollet, J.; Omi, P. N. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire*. 11: 1-10.
- Raymond, C. L.; Peterson, D. L. 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. *Canadian Journal Forest Research*. 35: 2981-2995.
- Raphael, M. G.; White, M. 1984. Use of snags by cavity-nesting birds in the Sierra Nevada. *Wildlife Monographs*. 86: 1-66.
- Reinhardt, E. D.; Ryan, K. C. 1998. Analyzing effects of management actions including salvage, fuel treatment, and prescribed fire on fuel dynamics and fire potential. In: Pruden, T. L.; Brennan, L. A. eds. *Fire in ecosystem management: shifting the paradigm from suppression to prescription*. Tall Timbers Fire Ecology Conference Proceedings. No. 20. Tall Timbers Research Station, Tallahassee, FL. 206-209.
- Saab, V.; Dudley, J. 1998. Responses of cavity-nesting birds to stand-replacement fire and salvage logging in ponderosa pine/ Douglas-Fir forests of southwestern Idaho. Res. Pap. RMRS-RP-11. Ogden, UT: U.S. Department of Agriculture, Forest Service. Rocky Mountain Research Station. 17 p.
- Saab, V. A.; Dudley, J.; Thompson, W. L. 2004. Factors influencing occupancy of nest cavities in recently burned forests. *Condor*. 106: 20-36.
- Saab, V. A.; Powell, H. D. W. 2005. Fire and Avian Ecology in North America: process influencing pattern. *Studies in Avian Biology*. 30: 1-13.
- Saab, V.A.; Powell, H. D. W.; Kotliar, N. B.; Newlon, K. R. 2005. Variation in fire regimes of the Rocky Mountains: implications for avian communities and fire management. *Studies in Avian Biology*. 30: 76-96.
- SAS Institute. 2003. SAS (9.1) PROC MIXED. SAS Institute Inc., Cary, NC.
- Schoennagel, T.; Veblen, T. T.; Romme, W. H. 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. *BioScience*. 54: 661-676.
- Scott, V. E. 1979. Bird response to snag removal in ponderosa pine. *Journal of Forestry*. 77: 26-28.
- Shinneman, D. J.; Baker, W. L. 1997. Nonequilibrium dynamics between catastrophic disturbances and old-growth forests in ponderosa pine landscapes of the Black Hills. *Conservation Biology*. 11: 1276-1288.
- Stephens, S. L.; Moghaddas, J. J. 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. *Forest Ecology and Management*. 215: 21-36.
- Szaro, R. C.; Severson, K. E.; Patton, D. R. eds. 1988. *Management of amphibians, reptiles, and small mammals in North America*. Gen. Tech. Rep. RMRS-GTR-166. Fort Collins, CO: U.S. Forest Service, Forest Service, Rocky Mountain Research Station.

- Thies, W. G.; Westlind, D. J.; Loewen, M. 2005. Season of prescribed burn in ponderosa pine forests in eastern Oregon: impact on pine mortality. *International Journal of Wildland Fire*. 14: 223-231.
- Tiedemann, A.; Klemmedson, J. O.; Bull, E. L. 2000. Solution of forest health problems with prescribed fire: are forest productivity and wildlife at risk. *Forest Ecology and Management*. 127: 1-18.
- U.S. Department of Agriculture, Forest Service. 1996. Forest Service Handbook. Timber Management Control Handbook. FSH: 2409.21e.
- Veblen, T. T. 2000. Disturbance patterns in central Rocky Mountain forests. In: Knight, R. L.; Smith, F. W.; Buskirk, S.W.; Romme, W. H.; Baker, W. L. eds. *Forest fragmentation in the southern Rocky Mountains*. University Press of Colorado, Niwot, CO. 33-56.
- Zar, J. 1999. *Biostatistical analysis*. Prentice-Hall, Upper Saddle River, NJ. 718 p.

Biomass Consumption During Prescribed Fires in Big Sagebrush Ecosystems

Clinton S. Wright¹ and Susan J. Prichard²

Abstract—Big sagebrush (*Artemisia tridentata*) ecosystems typically experience stand replacing fires during which some or all of the ignited biomass is consumed. Biomass consumption is directly related to the energy released during a fire, and is an important factor that determines smoke production and the effects of fire on other resources. Consumption of aboveground biomass (fuel) was evaluated for a series of operational prescribed fires in big sagebrush throughout the interior West. Pre-burn fuel characteristics (composition, amount, and structure), fuel conditions (live and dead fuel moisture content), and environmental conditions (weather and topography) affected fire behavior and subsequent fuel consumption. Total aboveground biomass consumption varied from 1.6 to 22.3 Mg ha⁻¹ (18 to 99 %) among the 17 experimental areas. Multiple linear regression and generalized linear modeling techniques were used to develop equations for predicting fuel consumption during these prescribed fires. Pre-burn fuel loading, which is influenced by season of burn, site productivity, time-since-last-fire, and grazing is the most important predictor of fuel consumption. Use of fire in big sagebrush is desirable for several reasons, including wildlife habitat improvement, livestock range improvement, fire hazard abatement, and ecosystem restoration.

Keywords: *Artemisia tridentata*, big sagebrush, fire effects, fuel consumption

Introduction

Research to quantify and model fuel consumption during wildland fires has been conducted in managed and unmanaged forest types throughout the United States (e.g., Ottmar 1983; Sandberg and Ottmar 1983; Little and others 1986; Brown and others 1991; Hall 1991; Albin and Reinhardt 1997; Reinhardt and others 1997; Myanishi and Johnson 2002), but is generally lacking or of limited scope in shrub-dominated ecosystems (for example, Sapsis and Kauffman 1991). Much of the existing fire research in shrub types has focused on fire behavior prediction in a limited number of shrub types (for example, Lindenmuth and Davis 1973; Green 1981; Brown 1982). Shrub-dominated ecosystems occur on hundreds of millions of hectares of private, state and federal lands in the United States. Sagebrush (*Artemisia* spp.) occurs on at least 38.5 million hectares in the interior West, making it one of the largest biomes in North America (Shiflet 1994). Sagebrush and other shrub-dominated types may be remotely located or they may occur at the wildland-rural/suburban/urban interface throughout their range. Many shrub-dominated ecosystems are home to sensitive, rare, threatened and endangered species, including numerous species of birds, mammals, mollusks, insects,

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

¹ Research Forester, USDA Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, Seattle, WA. cwright@fs.fed.us

² Research Ecologist, USDA Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, Seattle, WA.

plants, fish, reptiles and amphibians. In terms of sheer land area, proximity to populated areas, and wildlife habitat, research in shrub-dominated types addresses information needs for a diverse array of natural resource managers.

Increasing public awareness of environmental issues necessitates that resource managers fully evaluate regulatory requirements and potential impacts of land management decisions (in other words, no action, prescribed fire use, wildland fire use, grazing, mechanical treatment, chemical treatment, etc.) using the best available information. Where fire is concerned, quantification of fuel consumption is critical for evaluating fire severity (for example, Keely and others 2005), and for effectively modeling fire effects, including smoke emissions, regional haze, nutrient cycling, plant succession, species composition changes, plant/tree mortality, wildlife habitat restoration and maintenance, erosion, soil heating, and carbon cycling. Fuel consumption is the most critical variable for effectively evaluating and managing the consequences of prescribed and wildland fire as related to land management objectives.

Many sagebrush-dominated ecosystems in the western United States have experienced periodic, naturally occurring fire events (Miller and Rose 1999). Resource managers use prescribed fire as a multi-scale treatment for a number of specific purposes, including fuel and fire hazard reduction, wildlife habitat improvement, and ecosystem restoration. In contrast to forested systems where a large proportion of the fuelbed is composed of dead and down organic matter, in sagebrush-dominated ecosystems, the fuelbed is composed almost entirely of living (and standing dead) vegetation. Prior to the application of fire in forests and shrublands it is desirable to gauge the likelihood of treatment success (in other words, desired change in vegetation or fuel structure) by predicting fuel consumption. Change in the vegetation structure (that is, fuel composition, amount and arrangement) is often the most significant measure of treatment success. If resource managers in the sagebrush biome are to develop effective fire plans and prescriptions designed to meet desired objectives for terrestrial and atmospheric resources, research must quantify both fuel characteristics and fuel consumption during wildland fires.

Objective

The primary objective of our research was to develop models to predict biomass consumption in big sagebrush ecosystems using variables that are relatively easily measured or readily obtained. These fuel consumption models have been incorporated into the software CONSUME 3.0 (Prichard and others, in press). Development of consumption models for sagebrush ecosystems and their application in CONSUME 3.0 promotes more effective and informed use of emission production, fire effects, and wildfire/prescribed fire tradeoff models allowing for better wildland fire emissions and fire effects accounting and planning at a variety of scales.

Methods

Data were collected at 17 locations on a series of operational prescribed fires in big sagebrush (*A. tridentata*) ecosystems in southeastern Oregon, northwestern Nevada, northwestern Wyoming, and northern California (table 1). Sampling for fuel consumption occurred on gentle slopes (0 to 15 percent slope) of all

Table 1—Site information for experimental sagebrush burns.

Site Name	# Sites	Latitude	Longitude	Elevation	Slope	State	Admin. Unit ^a
Flook Lake	3	42° 36'	119° 32'	1539-1542 m	0 %	OR	USFWS1
Stonehouse	1	42° 56'	118° 26'	1937 m	15 %	OR	BLM1
V-Lake	5	42° 28'	118° 44'	2018-2056 m	0-15 %	OR	Private
Gold Digger Pass	2	41° 46'	121° 34'	1331-1346 m	0-5 %	CA	NPS
Escarpment	2	41° 52'	119° 40'	1672-1693 m	0-5 %	NV	USFWS2
Sagehen	1	41° 56'	119° 15'	1717 m	0 %	NV	USFWS2
Heart Mountain	3	44° 42'	109° 09'	1764-1823 m	0-15 %	WY	BLM2

^aUSFWS1 = U.S. Fish and Wildlife Service, Hart Mountain National Antelope Refuge; USFWS2 = U.S. Fish and Wildlife Service, Sheldon National Wildlife Refuge; BLM1 = Bureau of Land Management, Burns, OR; BLM2 = Bureau of Land Management, Cody, WY; Private = Roaring Springs Ranch; NPS = Lava Beds National Monument.

aspects at elevations ranging from 1,331 to 2,056 m. Sites were selected to represent a broad range of coverage and biomass of standing big sagebrush of all three recognized subspecies: Wyoming big sagebrush (*A. t. ssp. wyomingensis*), mountain big sagebrush (*A. t. ssp. vaseyana*), and basin big sagebrush (*A. t. ssp. tridentata*). Big sagebrush subspecies occur on sites that follow a gradient of increasing precipitation; Wyoming big sagebrush occupies the driest sites (20 to 32 cm annual precipitation), mountain big sagebrush occupies the wettest sites (31 to 149 cm annual precipitation) and basin big sagebrush is found on intermediate sites (Francis 2004). Experimental areas were embedded within larger operational units, and were burned under a variety of environmental and fuel moisture conditions during the fall of 2001 (September 23 to October 25) and spring of 2002 (March 21; table 2).

Data Collection

Fuel Characterization and Consumption—A regular grid of 2 × 2 m plots (or 1.5 × 1.5 m, if vegetation was particularly large or dense) was used to determine fuel loading and composition in a relatively uniform stand or patch of big sagebrush. A total of 36 plots were numbered sequentially; nine plots each were located every 7.6 m along four 76.2-m long transects that

Table 2—Weather and fuel moisture information for experimental sagebrush burns.

Site name	Subsp. ^a	Weather			Fuel moisture		
		Temp.	RH	Windspeed	Grass	Live sage foliage	Dead sage 10hr ^b
		°C	percent	km hr ⁻¹	-----	percent -----	
Flook Lake	W	17.2-17.8	17-34	12.1-12.9	9.8-10.2	59.9-61.8	9.2
Stonehouse	M	7.2	40	6.4	29.9	78.7	8.4
V-Lake	M	21.1-23.9	22-28	3.2-12.1	19.9-38.7	60.6-74.9	2.8-6.2
Gold Digger Pass	M	16.7	25-26	7.2	13.7	71.9	7.7
Escarpment	W-B	17.8	35	6.4	10.6	68.9	6.8
Sagehen	B	17.2	23	16.1	14.5	77.1	10.8
Heart Mountain	M-W	16.1-20.6	24-28	4.0-12.1	30.3	73.6	5.7

^aW = Wyoming (*A. wyomingensis*); M = Mountain (*A. vaseyana*); B = Basin (*A. tridentata*).

^b10hr fuel particles are 0.64 – 2.54 cm in diameter.

were spaced 10 to 20 m apart (no plots were placed at transect endpoints). Odd- or even-numbered plots were randomly selected to be destructively sampled before the fire; remaining plots were destructively sampled after the fire. Fuels were characterized by clipping at ground level or collecting, drying and weighing all standing biomass or surface fuels rooted or located inside the plot frame. Biomass was separated into the following categories in the field: grasses, forbs, live sagebrush, dead sagebrush, shrubs other than sagebrush (hereafter referred to as 'other shrubs'), dead and down woody fuels by size class (1hr, 10hr, 100hr, and 1000hr¹), and litter. Dead branches and twigs on living sagebrush plants were removed and included in the dead sagebrush category. Grasses, forbs, other shrubs, dead and down woody fuels, and litter were collected, returned to the laboratory, dried for a minimum of 48 hours at 100 °C, and weighed to determine oven-dry fuel loading by category on an area basis. Sagebrush was harvested, separated into live and dead biomass, and weighed in the field. One or two complete branches from each field sample were collected in heavy-gauge plastic bags with airtight seals. These subsamples were weighed shortly after collection, returned to the laboratory, dried for a minimum of 48 hours at 100 °C, and weighed to determine live and dead sagebrush moisture content per plot. The following formula was used to adjust sagebrush field weight to oven-dry weight:

$$\frac{\text{moisture subsample dry weight}}{\text{moisture subsample wet weight}} \times \text{undried field weight} = \text{oven-dry weight} \quad (1)$$

Pre-fire coverage by category (grass, forbs, sagebrush, other shrubs, litter) was measured using the line intercept method (Canfield 1941) along the full length of all four 76.2-m long layout transects. Grass, forb, sagebrush, and other shrub heights were measured at points every 7.6 m along the full length of all four transects. As most fires were patchy, coverage of the area burned during the fire was measured along parallel transects that were offset 3 m from the original layout to avoid sampling in areas that had been destructively sampled before the fire.

Fuel consumption was calculated by subtracting average post-burn biomass from average pre-burn biomass for sagebrush, and by multiplying average pre-burn biomass by the percentage of the area burned for the other fuel categories. Based on post-fire field observations, we assumed that all non-sagebrush biomass was consumed in areas that were burned.

Day of Burn Fuel Moisture and Weather—Five to 10 grab samples of grass, sagebrush foliage, and standing dead sagebrush in 1hr, 10hr, and 100hr size classes were collected in the interplot area prior to the burning of each experimental area. A single set of fuel moisture samples was collected to represent multiple sites if they were relatively close to one another, and being burned at or around the same time. Samples of approximately 50 to 400 g each were collected in heavy gauge, plastic bags with airtight seals, weighed immediately after collection, returned to the laboratory, oven-dried for a minimum of 48 hours at 100 °C, and weighed to determine fuel moisture content on a dry weight basis. Weather conditions during the burning period were measured every 15 to 30 minutes using a sling psychrometer (temperature and relative humidity) and an electronic pocket weather meter (temperature, relative humidity, windspeed 2 m aboveground). Weather conditions were

¹ 1hr, 10hr, 100hr, and 1000hr timelag fuels are defined as woody material ≤0.64 cm, 0.64-2.54 cm, 2.55-7.62 cm, and >7.62 cm in diameter, respectively.

also measured with a portable weather station (temperature, relative humidity, windspeed 2 m aboveground) logging 15-minute average values at several of the experimental locations. Temperature and relative humidity measurements taken using the sling psychrometer and windspeed measurements taken using the pocket weather meter were used preferentially, as these are the tools available to practitioners on the fireline.

Ignition—Sites were ignited during the course of daily prescribed burning operations. Most experimental sites were ignited by hand with drip torches, although a few areas were aerially ignited using incendiary plastic spheres containing chemicals that undergo a rapid exothermic reaction when mixed (ethylene glycol and potassium permanganate). Experimental areas typically burned in a heading or flanking fire.

Data Analysis

Model Development—Pre-burn coverage and height data, and coverage and height data from the Natural Fuels Photo Series (Ottmar and others 2000) were combined to develop a model to estimate sagebrush loading. Models to predict consumption of biomass were constructed from the suite of fuel characteristics and environmental variables measured before and during the fires. A simple correlation matrix of all variables measured as part of this study identified those that were most promising for constructing the predictive models. Forward and backward stepwise multiple linear regression (Neter and others 1990) was used to identify preliminary models; expert opinion was used to select the final models. Criteria for model selection included parsimony as well as the presence of reasonable physical explanations for a given variable's inclusion in the full model. A generalized linear model (GLM; McCullagh and Nelder 1989) of the binomial family was also developed for predicting the proportion of biomass consumed using the same variables included in the multiple linear regression model. The binomial GLM predicts proportional shrub consumption between [0,1] and therefore avoids predictions of fuel consumption that are either less than zero or greater than the pre-fire fuel amount. The GLM was created in S-plus (Insightful 2002) and programmed into the CONSUME 3.0 software (Prichard and others, in press). Both models' predictive capabilities were compared to independent data sets reported by Kauffman and Cummings (1989) and Sapsis and Kauffman (1991).

Results

Tables 3, 4, and 5 summarize pre-fire fuel loading, pre- and post-fire coverage, and fuel consumption, respectively. Total aboveground pre-fire biomass ranged from 5.3 to 22.6 Mg ha⁻¹; sites dominated by mountain big sagebrush tended to have the most aboveground biomass. Pre-fire sagebrush loading ranged from 4.4 to 20.2 Mg ha⁻¹ with site coverage of 14 to 67 percent. All, live and dead sagebrush represented from 46 to 92, 25 to 64, and 20 to 56 percent of the total site biomass, respectively; total sagebrush biomass was >80 percent of total biomass for 16 out of 17 sites. Mean sagebrush height ranged from 0.3 to 0.9 m, although many plants were taller than the mean height. Pre-fire herbaceous vegetation and other shrub loading (and coverage) ranged from 0.1 to 0.6 Mg ha⁻¹ (5 to 38 percent) and zero to 3.7 Mg ha⁻¹ (0 to 19 percent), respectively. Surface fuel loading ranged from 0.3 to 2.7 Mg ha⁻¹.

Table 3—Pre-fire fuel loading for experimental sagebrush burns.

Site name	Loading						All fuels
	Herbaceous vegetation	Live sagebrush	Dead sagebrush	Other shrubs	All vegetation	Surface fuels ^a	
----- <i>Megagrams hectare⁻¹</i> -----							
Flook Lake 1	0.290	5.521	5.623	0.002	11.435	0.866	12.300
Flook Lake 2	0.109	7.141	5.763	0.000	13.013	1.523	14.536
Flook Lake 3	0.106	6.087	4.214	0.063	10.471	0.714	11.185
Stonehouse	0.614	4.621	1.995	0.580	7.810	2.211	10.021
V-Lake A	0.156	11.113	5.177	0.440	16.885	1.975	18.860
V-Lake 1	0.273	7.919	3.514	0.236	11.942	1.974	13.916
V-Lake 2	0.206	9.207	3.787	0.229	13.430	1.052	14.481
V-Lake 3	0.158	3.239	1.162	0.043	4.602	0.672	5.274
V-Lake 4	0.224	11.062	3.635	0.312	15.233	1.122	16.356
Gold Digger 1	0.543	4.522	3.796	0.191	9.052	0.339	9.391
Gold Digger 2	0.570	6.348	3.396	0.000	10.314	0.511	10.825
Escarpment 1	0.310	3.094	2.652	3.723	9.780	2.709	12.488
Escarpment 2	0.251	7.619	6.626	0.031	14.527	1.562	16.088
Sagehen	0.078	6.081	10.919	0.035	17.112	2.231	19.343
Heart Mtn HM	0.393	12.709	7.492	0.000	20.594	1.994	22.588
Heart Mtn OT	0.411	4.520	2.937	0.409	8.277	0.992	9.269
Heart Mtn SC	0.361	5.531	3.193	0.003	9.088	0.968	10.056

^aIncludes litter and all dead and down woody fuels.**Table 4**—Pre- and post-fire coverage for experimental sagebrush burns.

Site name	Pre-fire coverage				Post-fire coverage	
	Herbaceous vegetation	sagebrush	Other shrubs	All vegetation	Area burned	Unburned sagebrush
----- <i>percentage</i> -----						
Flook Lake 1	10.8	35.9	0.2	46.8	32.7	21.5
Flook Lake 2	20.1	38.1	0.0	58.1	38.6	22.6
Flook Lake 3	4.6	29.0	0.2	33.8	36.9	24.6
Stonehouse	20.0	35.7	6.9	62.5	39.8	29.0
V-Lake A	20.0	49.8	6.1	75.8	50.6	21.9
V-Lake 1	12.3	43.9	9.3	65.4	74.6	13.8
V-Lake 2	14.8	43.2	3.7	61.7	53.8	21.3
V-Lake 3	15.1	34.5	1.5	51.2	23.9	20.0
V-Lake 4	23.0	59.5	3.1	85.6	96.9	1.6
Gold Digger 1	22.9	24.5	5.6	53.0	36.4	19.5
Gold Digger 2	23.7	30.3	2.6	56.6	60.4	10.7
Escarpment 1	13.7	13.5	19.1	46.3	75.9	4.3
Escarpment 2	22.0	35.1	0.5	57.6	78.2	7.2
Sagehen	5.0	43.3	5.9	54.2	14.5	33.1
Heart Mtn HM	37.6	66.5	0.3	98.3	98.4	0.6
Heart Mtn OT	34.3	29.7	2.7	66.7	94.8	0.5
Heart Mtn SC	31.5	42.0	0.1	73.6	99.8	0.3

Table 5—Fuel consumed during experimental sagebrush burns.

Site name	Consumption					
	Herbaceous vegetation	Sagebrush	Other shrubs	All vegetation	Surface fuels ^a	All fuels
	----- Megagrams hectare ⁻¹ (percentage of pre-fire loading) -----					
Flook Lake 1	0.097 (33.6)	3.132 (28.1)	0.001 (33.6)	3.230 (28.2)	0.291 (33.6)	3.521 (28.6)
Flook Lake 2	0.042 (38.6)	4.020 (31.2)	—	4.062 (31.2)	0.588 (38.6)	4.650 (32.0)
Flook Lake 3	0.040 (38.0)	4.999 (48.5)	0.024 (38.0)	5.064 (48.4)	0.271 (38.0)	5.335 (47.7)
Stonehouse	0.246 (40.0)	1.992 (30.1)	0.232 (40.0)	2.469 (31.6)	0.885 (40.0)	3.354 (33.5)
V-Lake A	0.082 (53.0)	9.750 (59.9)	0.233 (53.0)	10.065 (59.6)	1.046 (53.0)	11.112 (58.9)
V-Lake 1	0.205 (75.3)	7.571 (66.2)	0.177 (75.3)	7.954 (66.6)	1.486 (75.3)	9.440 (67.8)
V-Lake 2	0.129 (62.4)	9.457 (72.8)	0.143 (62.4)	9.728 (72.4)	0.656 (62.4)	10.384 (71.7)
V-Lake 3	0.050 (31.6)	1.322 (30.0)	0.013 (31.6)	1.385 (30.1)	0.212 (31.6)	1.597 (30.3)
V-Lake 4	0.218 (97.2)	13.648 (92.9)	0.304 (97.2)	14.170 (93.0)	1.091 (97.2)	15.260 (93.3)
Gold Digger 1	0.201 (37.0)	4.660 (56.0)	0.070 (37.0)	4.931 (54.5)	0.125 (37.0)	5.057 (53.8)
Gold Digger 2	0.346 (60.7)	5.655 (58.0)	—	6.001 (58.2)	0.310 (60.7)	6.311 (58.3)
Escarpment 1	0.242 (78.1)	3.116 (54.2)	2.906 (78.1)	6.264 (64.1)	2.114 (78.1)	8.379 (67.1)
Escarpment 2	0.197 (78.6)	12.662 (88.9)	0.024 (78.6)	12.884 (88.7)	1.227 (78.6)	14.111 (87.7)
Sagehen	0.016 (20.5)	2.737 (16.1)	0.007 (20.5)	2.761 (16.1)	0.763 (34.2)	3.524 (18.2)
Heart Mtn HM	0.390 (99.2)	19.916 (98.6)	0.000 (99.2)	20.306 (98.6)	1.978 (99.2)	22.284 (98.7)
Heart Mtn OT	0.411 (100.0)	7.341 (98.4)	0.409 (100.0)	8.161 (98.6)	0.992 (100.0)	9.153 (98.8)
Heart Mtn SC	0.361 (100.0)	8.525 (97.7)	0.003 (100.0)	8.889 (97.8)	0.968 (100.0)	9.857 (98.0)

^aIncludes litter and all dead and down woody fuels.

Total aboveground biomass consumption varied from 1.6 to 22.3 Mg ha⁻¹ (18 to 99 percent) among the 17 experimental areas, with 15 to 100 percent of the experimental area burned. Most fires were patchy, although in excess of 90 percent of the area burned for four of the 17 sites. Post-fire coverage of unburned live sagebrush ranged from <1 to 33 percent. Fire spread was most limited in the single spring burn (Sagehen) despite temperature, relative humidity, and windspeed conditions similar to the fall burns (all others). Five out of seven of the study sites where fire burned less than 40 percent of the experimental area had dead 10hr sagebrush fuel moisture values in excess of eight percent. Fuel consumption was highest at sites where dead 10hr fuel moisture was 6.1 percent and less.

Multiple linear regression and generalized linear models are reported in table 6. Percentage of area burned and pre-burn sagebrush loading were strong predictors of sagebrush consumption (fig. 1a). Similarly, percentage of area burned and pre-burn loading of non sagebrush fuels were predictors of non sagebrush consumption (fig. 1b). Pre-burn coverage of herbaceous vegetation, slope, windspeed, 10hr fuel moisture were chosen as variables to predict percentage of area blackened (fig. 2).

Because of our relatively small sample size (n=17), we chose to retain all data points in the model building data set. However, using the generalized linear and multiple linear regression models, predicted total fuel consumption averaged within ± 3.1 and ± 1.9 percent, respectively, of observed values for four fall prescribed fires, and within ± 11.9 and ± 12.6 percent, respectively, of observed values for four spring fires measured by Kauffman and Cummings (1989) and Sapsis and Kauffman (1991).

Table 6—Regression equations for sagebrush loading, sagebrush and non sagebrush consumption, and area burned. The generalized linear model (GLM) gives the proportion of the area burned or biomass consumed and follows the form: $Y = \text{EXP}(y)/(1+\text{EXP}(y))$; multiply Y_{AB} by 100 to get AB, Y_{C_s} by L_s to get C_s , and Y_{C_n} by L_n to get C_n .

Equations	a	b ₁	b ₂	b ₃	R ²
Multiple Linear Regression					
$L_s = a + b_1(P_s) + b_2(H_s)$	-1.364	0.292	1.365		0.85
$AB = a + b_1(P_h) + b_2(FM) + b_3(W \times S)$	30.582	1.951	-4.369	1.737	0.69
$C_s = a + b_1(L_s) + b_2(AB)$	-7.171	0.681	0.111		0.87
$C_n = a + b_1(L_n) + b_2(AB)$	-1.056	0.706	0.016		0.96
Generalized Linear Model					
$Y_{AB} = a + b_1(P_h) + b_2(FM) + b_3(W \times S)$	-1.734	0.114	-0.209	0.110	0.75 ^a
$Y_{C_s} = a + b_1(L_s) + b_2(AB)$	-2.657	0.043	0.047		0.82 ^a
$Y_{C_n} = a + b_1(L_n) + b_2(AB)$	-2.206	-0.050	0.052		0.89 ^a

^a(null deviance - residual deviance) ÷ null deviance; (analogous to R² for GLM)

Symbols:

L_s = pre-burn loading of sagebrush, Mg ha⁻¹;

L_n = pre-burn loading of non sagebrush biomass, Mg ha⁻¹;

P_s = pre-burn coverage of sagebrush;

H_s = pre-burn height of sagebrush, meters;

AB = area burned, percentage of total area;

P_h = pre-burn coverage of herbaceous vegetation, percentage;

FM = day of burn 10hr fuel moisture, percentage by dry weight;

W = day of burn windspeed, km hr⁻¹;

S = slope category, <5%=1, 5-15%=2, 16-25%=3, 26-35%=4, >35%=5;

C_s = consumption of sagebrush, Mg ha⁻¹;

C_n = consumption of non sagebrush, Mg ha⁻¹.

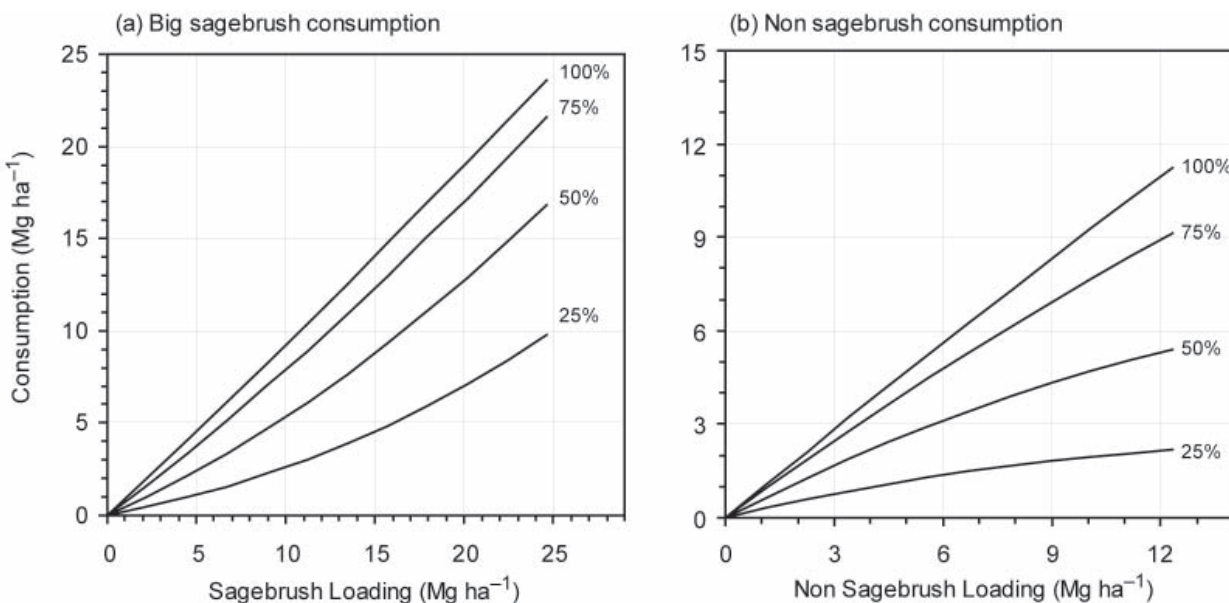


Figure 1—Generalized linear models showing (a) sagebrush and (b) non sagebrush consumption as a function of loading at 25, 50, 75, and 100 percent of area burned (lines).

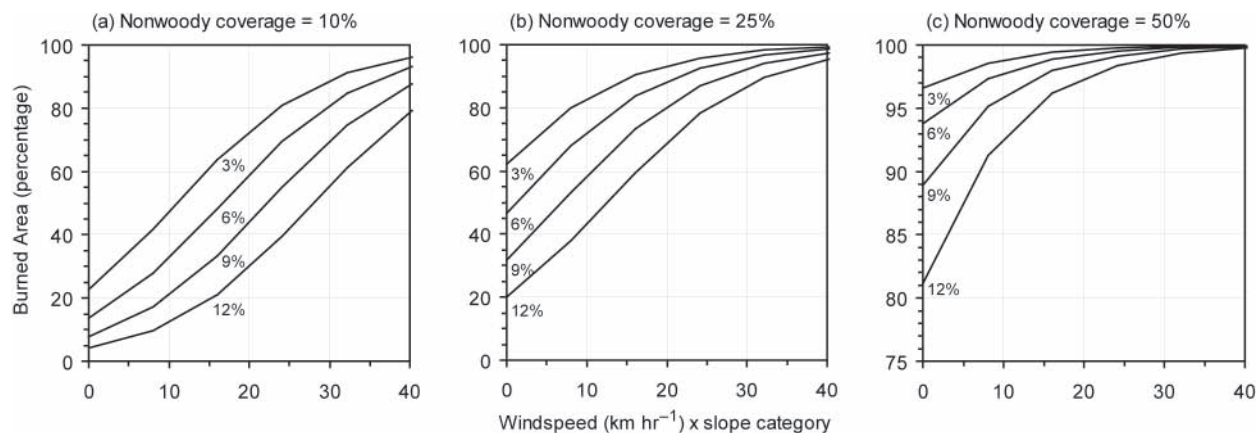


Figure 2—Generalized linear model showing area burned as a function of windspeed \times slope category at 3, 6, 9, and 12 percent 10hr fuel moisture content (lines) where herbaceous vegetation coverage is (a) 10 percent, (b) 25 percent, and (c) 50 percent.

Discussion

Two conditions contribute to fuel consumption (and post-fire fuel loading); partially consumed fuel particles, and fuel left in unburned patches. Fuel loading and coverage, fuel moisture, weather (windspeed), and site characteristics (slope) are incorporated in the predictive equations reported here. These equations encapsulate all of the consumption that occurs because of partial burning of fuels and patchy burning of an area. Sites where fire spread was patchier and fire carried through less of the plot area typically experienced lower overall fuel consumption, although a high proportion of the fuels in the burned areas may have consumed.

The final models are relatively simple and incorporate predictor variables for which users are likely to have, or can readily acquire the necessary data. Pre-burn biomass is a key variable for predicting fuel consumption. Biomass can be estimated from locally available inventory data, from fuels assessments using photo guides (for example, Ottmar and others 1998, 2000) or calculated using the equation for estimating sagebrush biomass (L_s) from sagebrush coverage (P_s) and height (H_s ; table 6). While managers and planners typically do not have biomass data at their disposal, they often have coverage and height data, or can easily acquire it from a variety of sources. Percentage of area burned is the other key variable for predicting fuel consumption. We include an equation to predict this value (AB), again, based on data that fire managers and planners are likely to have at their disposal and routinely include in prescribed fire burn plans and prescriptions, including windspeed (W), slope (S), and 10hr fuel moisture (FM; table 6).

Users of CONSUME 3.0 can easily predict how environmental, site, and fuel conditions will affect potential percentage of area burned and fuel consumption. This is a tool that can be used for developing burning prescriptions that meet specific management objectives. For example, if one objective of a prescribed fire project is to create a mosaic of burned and unburned veg-

etation in a specific area for wildlife habitat improvement, users can modify windspeed and fuel moisture inputs until the model yields the desired amount or range of percentage of area burned, thereby defining the prescription parameters. Similarly, a desired percentage of area burned can then be used as an input along with information about site biomass, to predict potential fuel consumption and smoke emissions or other fire effects.

Energy (heat) is required to drive off fuel moisture, to heat fuel particles to pyrolysis and combustion temperatures, and to sustain flaming combustion. Dead 10hr fuel moisture content is an indicator of how readily combustion occurs, how effectively fire spreads from particle to particle and from dead to live fuels, and subsequently how much fuel consumes. Increasing amounts of fuel become available to burn as live and dead fuel moisture decline, however, once fuel moisture has fallen below a critical value, weather and fuel loading appear to become the elements affecting fuel consumption. Where sufficient amounts of fuel are available to burn, prevailing weather conditions (windspeed in our model) appear critical for determining fire spread and fuel consumption. The effects of windspeed can be exacerbated or mitigated to some degree by slope. The multiplier for slope incorporated in the windspeed \times slope variable in the equation for predicting area burned is comparable to values suggested by Brown (1982). Poor fuel consumption conditions (elevated fuel moisture, elevated relative humidity, low windspeeds, lack of carrier fuels, etc.) may be mitigated to some degree by an aggressive burning operation. If enough fire can be introduced to the site at once, fire spread can be facilitated, and fuel consumption increased. Use of heli-torches, terra-torches and large numbers of hand igniters can be effective for mass ignition.

Individual plant height, plant to plant spacing, interplant "understory" vegetation amount, overall biomass, and live fuel:dead fuel ratios all may have an effect on how well fire spreads, how much heat and energy are generated, how long flaming and smoldering combustion persist, and therefore how much fuel consumes. Other weather variables, such as temperature, solar insolation (or shading), and relative humidity; and other fuel characteristics, such as live fuel moisture, likely are also important, although they were not useful as predictors of fire spread and fuel consumption given their limited range in our data set. A larger data set with a greater range of values may help identify if or how they are correlated with fuel consumption.

The predictive models reported here are empirical. They represent correlations among variables, and not cause and effect relationships. However, variables were included in the various models only if there was a reasonable physical explanation. For example, cover of herbaceous vegetation was included in the model to predict how much of an area was likely to burn, as the grasses and forbs growing between and under individual sage plants provide a vector for fire to spread from plant to plant. Similarly, windspeed was included as it influences convective heat transfer and flame contact among adjacent shrubs and other fuel particles.

Fuel characterization, fuel moisture, site characterization and onsite weather sampling during the burning experiments allowed us to develop models for predicting fuel consumption that will be useful to fire managers and planners. The ability to predict fuel consumption under varying environmental conditions will facilitate prescription development, burn planning and burn scheduling. The tools available in CONSUME 3.0 will allow resource managers to better assess landscapes for opportunities and hazards, and to develop science-based treatment and mitigation strategies to most effectively manage fuel consumption, fire effects and smoke production.

Acknowledgments

This research was supported by the Joint Fire Science Program and the National Fire Plan. Roger Ottmar, David L. Peterson, and Donald McKenzie reviewed the manuscript.

Literature Cited

- Albini, F. A.; Reinhardt, E. D. 1997. Improved calibration of a large fuel burnout model. *International Journal of Wildland Fire*. 7: 21-28.
- Brown, J. K. 1982. Fuel and fire behavior prediction in big sagebrush. Res. Pap. INT-290. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 10 p.
- Brown, J. K.; Reinhardt, E. D.; Fischer, W. C. 1991. Predicting duff and woody fuel consumption in northern Idaho prescribed fires. *Forest Science*. 37: 1550-1566.
- Canfield, R. H. 1941. Application of the line interception method in sampling range vegetation. *Journal of Forestry*. 39: 388-394.
- Francis, J. K., ed. 2004. *Wildland shrubs of the United States and its Territories: thamnisc descriptions: volume 1*. Gen. Tech. Rep. IITF-26. San Juan, PR and Fort Collins, CO: U.S. Department of Agriculture, Forest Service, International Institute of Tropical Forestry and Rocky Mountain Research Station. 830 p.
- Green, L. R. 1981. Burning by prescription in chaparral. Gen. Tech. Rep. PSW-51. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 36 p.
- Hall, J. 1991. Comparison of fuel consumption between high and moderate intensity fires in logging slash. *Northwest Science*. 64(4): 158-165.
- Insightful. 2000. S-PLUS 6.1 for Windows. Seattle, WA: Insightful Corporation.
- Kauffman, J. B.; Cummings, D. L. 1989. Fuel loads and biomass consumption during spring and fall prescribed fires in central Oregon rangeland ecosystems. Unpublished report on file at the U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, Seattle, WA.
- Keely, J. E.; Fotheringham, C. J.; Baer-Keely, M. 2005. Determinants of postfire recovery and succession in Mediterranean-climate shrublands of California. *Ecological Applications*. 15(5): 1515-1534.
- Lindenmuth, A. W., Jr.; Davis, J. R. 1973. Predicting fire spread in Arizona's oak chaparral. Res. Pap. RM-101. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 11 p.
- Little, S. N.; Ottmar, R. D.; Ohmann, J. L. 1986. Predicting duff consumption from prescribed burns on conifer clearcuts in western Oregon and western Washington. Res. Pap. PNW-362. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 29 p.
- McCullagh, P.; Nelder, J. A. 1989. *Generalized Linear Models*. London, UK: Chapman and Hall. 511 p.
- Miller, R. F.; Rose, J. A. 1999. Fire history and western juniper encroachment in sagebrush steppe. *Journal of Range Management*. 52: 550-559.
- Myanishi, K.; Johnson, E. A. 2002. Process and patterns of duff consumption in the mixedwood boreal forest. *Canadian Journal of Forest Research*. 32: 1285-1295.

- Neter, J.; Wasserman, W.; Kutner, M. H. 1990. Applied linear statistical models: regression, analysis of variance, and experimental designs. 3rd edition. Boston, MA: Richard D. Irwin, Inc. 1181 p.
- Ottmar, R. D. 1983. Predicting fuel consumption by fire stages to reduce smoke from slash fires. In: Proceedings of the Northwest Forest Fire Council Annual Meeting; November 21-22, 1983; Olympia, WA. 20 p.
- Ottmar, R. D.; Vihnanek, R. E.; Wright, C. S. 1998. Stereo photo series for quantifying natural fuels. Volume I: mixed-conifer with mortality, western juniper, sagebrush, and grassland types in the interior Pacific Northwest. PMS 830. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center. 73 p.
- Ottmar, R. D.; Vihnanek, R. E.; Regelbrugge, J. 2000. Stereo photo series for quantifying natural fuels. Volume IV: pinyon-juniper, sagebrush, and chaparral types in the Southwestern United States. PMS 833. Boise, ID: National Wildfire Coordinating Group, National Interagency Fire Center. 97 p.
- Prichard, S. J.; Ottmar, R. D.; Anderson, G. K. [In press]. Consume 3.0 User's Guide. Gen. Tech. Rep. PNW-GTR-xxx. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.
- Reinhardt, E. D.; Keane, R. E.; Brown, J. K. 1997. First Order Fire Effects Model: FOFEM 4.0, user's guide. Gen. Tech. Rep. INT-GTR-344. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 65 p.
- Sandberg, D. V.; Ottmar, R. D. 1983. Slash burning and fuel consumption in the Douglas-fir subregion. In: Seventh Conference on Fire and Forest Meteorology; April 25-28, 1983; Fort Collins, CO. pp. 90-93.
- Sapsis, D. B.; Kauffman, J. B. 1991. Fuel consumption and fire behavior associated with prescribed fires in sagebrush ecosystems. Northwest Science. 65(4): 173-179.
- Shiflet, T. N., ed. 1994. Rangeland cover types of the United States. Denver, CO: Society for Range Management. 152 p.

The Lick Creek Demonstration — Forest Renewal Through Partial Harvest and Fire

Benjamin Zamora¹ and Melinda Martin²

Abstract—The Lick Creek Demonstration Site on the Pomeroy Ranger District, Umatilla National Forest, is a Joint Fire Science Program sponsored project to create a demonstration of the effects of fuels management on forest health. The project was initiated in 2001 and involved the integration of two levels of partial harvest with prescribed fire, a burn only treatment and an untreated control treatment. Biomass utilization was incorporated into the burn preparation following harvest. Objectives of the treatments were to improve stand composition and structure, reduce fuel levels, and enhance wildlife habitat. Units were harvested in 2001. Prescribed fire as applied in 2004. Monitoring of fuels and stand attributes was implemented in 2005. Harvest reduced overstory canopy coverage as much as 70%. Understory tree layers remained intact through the harvest but were significantly affected by the prescribed burn. Herbage production increased in areas of moderate fire intensity but showed little response in areas of high fire intensity. Less than 1% mortality was evident in 2005 among leave trees in the treatment units but tree conditions indicate future higher mortality. Fuels reduction was the most uniform in the commercial yarding treatments but was highly varied in the burn only treatments. Contractor revenue profits from the harvest and biomass fuel were modest and dependent on the provision of service contracts by the USFS Pomeroy Ranger District in addition to the release of the products to the contractors for independent sale.

Introduction

In 2000, the Joint Fire Science Program (JFSP) requested grant proposals for development of fuels management demonstration sites throughout the United States. The sites were to provide the public and research interests opportunity to observe the effects of fuels management involving prescribed fire on wildland ecosystems. The Pomeroy Ranger District of the Umatilla National Forest in southeastern Washington, in conjunction with Washington State University, received a grant from the JFSP to initiate the development of the Lick Creek Demonstration Site in the northern Blue Mountains of southeastern Washington. The project period was originally set for a three-year period from FY 2001 through FY 2003. The last of the project components was completed in 2005.

The overall goal of the Lick Creek project was to develop a demonstration of the application and effects of selective, partial harvest on mid-succession forest stands in combination with prescribed fire to enhance forest condition, amenities, and reduce wildfire hazard. Frequent and timely monitoring of the demonstration site would provide documentation to substantiate, clarify, and

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

¹ Associate Professor and Scientist, Natural Resource Sciences, Washington State University, Pullman, WA. bzamora@wsu.edu.

² Fire Planner, Fire/Fuels Management, Pomeroy Ranger District, USFS Umatilla National Forest, Pomeroy, WA.

explain anticipated ecological relationships and treatment effects throughout the demonstration site. The demonstration was to provide opportunity for general public examination and for the Pomeroy Ranger District to begin a long-term monitoring study of a fuels management strategy applied throughout the District.

Efforts to achieve public understanding and support of forest practices to rectify forest health issues is a priority in the Pomeroy Ranger District because of the sensitivity of the forest landscapes and the multiple interests in the public lands of the District. Successful implementation of any forest practice in the District is predicated on public support. The Lick Creek Demonstration is intended to show how forest practices can enhance forest landscapes for tree growth, wildlife habitat, and reduction of wildfire hazard.

The purpose of this proceedings paper is to provide a synopsis of the character and development of the demonstration site.

Objectives

The specific objectives of the project were (1) to implement four levels of viewable silvicultural and fuels management stand treatment on the Lick Creek site in a replicated manner, (2) prepare documentation of the treatments and treatment effects for public review, (3) initiate a long-term monitoring study of the site to document treatment effects to include response of leave trees, and (4) to assess the economic viability of small diameter timber harvest as a means of accomplishing silvicultural and fuels management objectives. The treatments would represent prescription strategies currently employed by District staff to address management of stand structure, species composition, and fuel conditions in mid-successional forest stands.

Site Location and Pretreatment Vegetation Character

The Lick Creek Demonstration Site lies within the Blue Mountains Physiographic Province of southeastern Washington (Fig. 1). The site is located in the eastern portion of the Pomeroy Ranger District of the Umatilla National Forest and centered at longitude 117.4833°, latitude 46.2333°. The general terrain of the area is a deeply dissected plateau to the south and east of the Snake River Canyon that traverses through southeastern Washington. The specific site terrain is a steep, dissected canyon slope between 4100-5100 ft elevation with aspects spanning northwest to northeast. Slopes average 50 to 60% across the entire site. The area is within the rain shadow cast by the central Blue Mountains ridge, thus is within a dry subhumid climate. Total annual precipitation is ± 35 inches with effective moisture varying according to topographic and soil conditions.

The vegetation of the site is a mosaic of forest stands interspersed with grassland sites on side-ridges and shallow soils (Fig. 2). Generally, two distinct zones of vegetation are distinguishable across the site. An upper canyon wall zone of the Douglas-fir/snowberry (*Pseudotsuga menziesii*/*Symphoricarpos albus*) and Douglas-fir/ninebark (*Pseudotsuga menziesii*/*Physocarpus malvaceus*) plant associations covers from $\frac{1}{4}$ to $\frac{1}{3}$ of the site slope surface (Johnson and Clausnitzer 1992). The width of this zone is dependent on

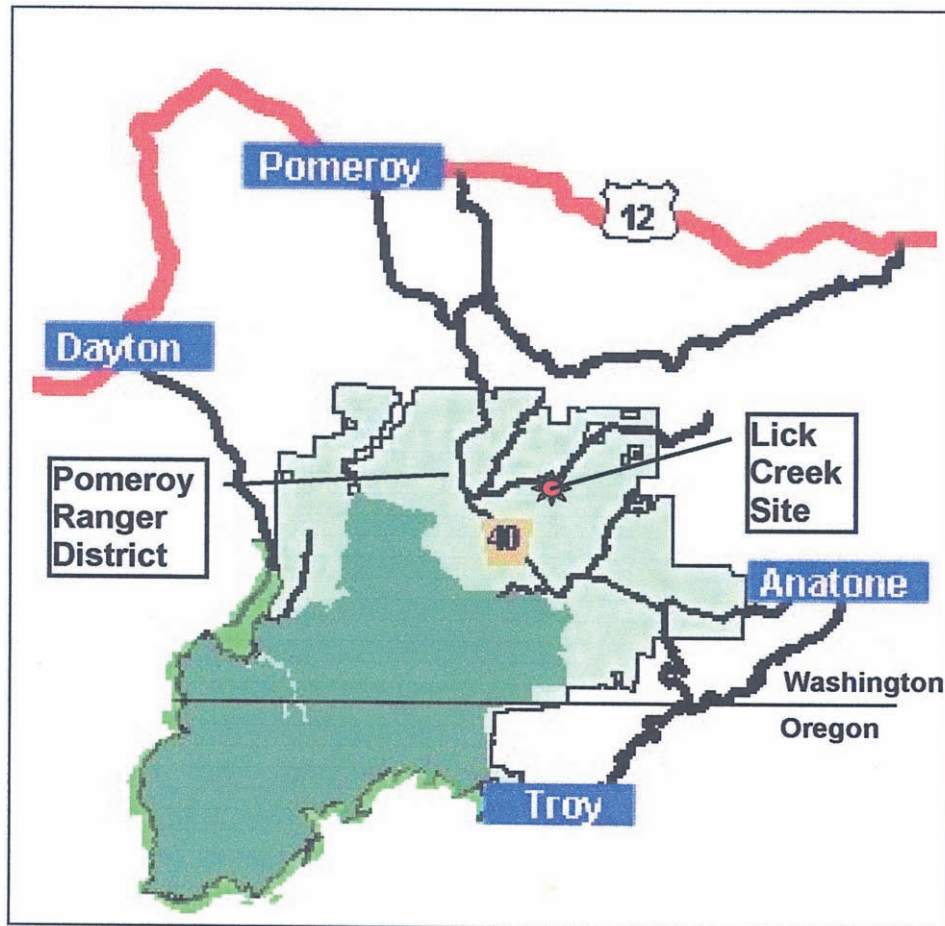


Figure 1—Location of the Lick Creek Demonstration Site in the Pomeroy Ranger District, Umatilla National Forest, southeastern Washington.



Figure 2—Pre-harvest photograph of the Lick Creek Demonstration Site looking east along the face of the site in 2000.

slope surface configuration with the narrowest portions associated with concave surfaces and the broadest portions associated with convex surfaces. The lower $\frac{2}{3}$ to $\frac{3}{4}$ of the canyon wall is dominated by the grand fir/twinflower (*Abies grandis*/ *Linnaea borealis*) plant association. Ponderosa pine (*Pinus ponderosa*) and western larch (*Larix occidentalis*) are the seral conifer tree species throughout the site.

The existing vegetation over the site prior to treatment generally reflected a mid-successional state (Fig. 3). Most of the area supported a sparse component of 100+ year-old trees of ponderosa pine, western larch, and Douglas-fir that formed an upper overstory layer with canopy cover ranging from 5-15%. Tree heights were 90 ft with average d.b.h. ranging from 20 to 32 inches. The majority of the leave trees in the harvest treatments were in this particular cohort. The bulk of the forest canopy was a deep mid-story tree layer composed predominantly of Douglas-fir (67%) and grand fir (24%) with sparse ponderosa pine (6%) and western larch (3%). Average height of trees within this layer ranged from 45 to 50 ft and averaged 9 to 11 inches d.b.h. Most of the merchantable timber came from this mid-story layer. A distinct third cohort of smaller trees with 3 to 6 inches d.b.h. occurred in the lower portion of the layer between 20 and 40 ft. These smaller trees composed 53% of the total tree density of the layer, and in combination with an understory layer of juvenile trees less than 3 inches d.b.h. and under 10 ft in height, formed the greatest barrier to light penetration to the ground surface.



Figure 3—Example of pre-harvest stand conditions in the Lick Creek Demonstration Site.

History of the Site

The Problem

The Lick Creek site was selectively harvested through several entries during the 1960's and early 1970's for large diameter sawlogs by means of a skyline system. No additional harvest or fuels treatment have occurred on the site since that time. There is no evidence of wildfire in the immediate drainage area of the site in the past 100+ years so the site represents a fire exclusion location. Stand development since the 1960's progressed to mid-successional stages of overstocked, nearly closed stands of small diameter, shade-tolerant Douglas-fir and grand fir. Competition from these shade-tolerant species reduced the abundance of shade-intolerant ponderosa pine and western larch. In addition, surface and ladder fuels were accumulating to the point of creating a severe surface and crown wildfire hazard (Fujishin 1998).

The drainage lies directly above a major Rocky Mountain elk winter range in the Asotin Creek watershed adjacent to the Snake River and is a significant part of a spring elk calving area and summer range for elk herds that utilize the Asotin Creek winter range. Stand closure of forests within the Lick Creek drainage was reducing the diversity and abundance of the understory and detrimentally affecting the quality of elk and wildlife habitat (Lorentz 1997).

The Solution

The prescription for stand management on the Lick Creek site revolved around the principal objectives of opening stands, shifting the balance of species composition to favor ponderosa pine and western larch, and reducing fuel loading (Bott 1998). Selective harvest and thinning from below combined with prescribed fire was prescribed to accomplish the objectives. The efficacy of these practices was considered to be well established (Agee 1996, Applegate and others 1997, Graham and others 1999, Williams and others 1993). Multiple entries over time with prescribed fire after harvest was thought necessary in order to ultimately achieve the objectives of the prescription (Martin 1998). The treatment effects of the combined practices were also expected to enhance wildlife habitat in general, and more specifically, the elk habitat of the site that is a central concern to several local public interest groups. Untreated wildlife leave units were integrated into the treatment design to serve a wildlife cover and travel corridors. Non-hazardous snags were left standing and a buffer zone was designated along the bottom of the Lick Creek drainage to protect watershed values and provide additional undisturbed wildlife cover.

Two primary concerns were identified in the development of the Lick Creek Demonstration prescription and are reflected as inclusions in the project objectives. These were (1) the effects of fire on leave trees and (2) the economic viability of small diameter timber harvest.

The mortality of large leave trees from prescribed fire across the Lick Creek site was a major concern (Martin 1998). Several recent studies have confirmed that mortality of trees from a prescribed fire increases as the depth of the duff layer around the base of the tree and the diameter of tree bole increases (Ryan and Frandsen 1995, Hille and Stephens 2005, Stephens and Finney 2002, Thies and others 2006). Documentation of the leave tree post-burn responses was designated as a priority element in the monitoring of the demonstration site.

The majority of the merchantable sawlog trees on the Lick Creek site grade as small diameter timber (5-9 inches d.b.h.), raising questions about the profitability of such a harvest to logging contractors and their interest in undertaking this kind of harvest option. Selective harvest and thinning of small diameter stands is being increasingly considered in the Interior Northwest as a means of reducing wildfire hazard, redistributing tree growth, and re-directing stand development (Wagner and others 1997, Baumgartner and others 2002). But questions remain about the financial viability of such harvest from the standpoint of product marketability and revenue and harvest costs (Johnson 1997, Wagner and others 1997). Harvest costs are affected by tree size and utilization with harvest costs inversely proportional to tree size—small-diameter trees result in small piece sizes with low volumes and are more costly to handle (Stokes and Klepac 1997). Johnson (1997) stated that an economical harvest of small trees is difficult to attain for two reasons—the cost per unit of volume to move the material increases dramatically as diameter of the volume decreases, and the value of the unit volume decreases as piece size decreases. Harvest costs increase with reduced road accessibility and conditions, less steeper and more complex terrain, smaller trees and higher density stands, limited opportunity to use less expensive mechanical yarding, and greater hauling distance. Ultimately, the availability of stable markets for multiple wood products from the harvest will dictate net profit from the harvest (Johnson 1997, Stokes and Klepac 1997). Documentation and evaluation of harvest and fuels treatment costs and product revenues to assess economic viability of the silvicultural and fuels management strategy was included as a primary objective of the project.

Methods

Treatment Design and Installation

The site was divided into three treatment units with wildlife habitat units left between some of the treatment units within the site boundaries (Fig. 4). A 150 ft buffer zone was maintained of at the bottom of the slope between the treatment units and Lick Creek. Each unit was divided into four subunits to replicate the treatment. The following four treatments were installed in each unit—two levels of harvest, a control, and a burn only treatment (Table 1). The replication subunits range in size from 6 to 17 acres, the size being dictated by uniformity of pre-harvest conditions and the facilitation of harvest and prescribed burning operations.

Treatment Schedule

Treatment planning, the timber cruise, and pre-logging stand inventory were conducted in 2000 and 2001. Harvest of the site was completed during the winter of 2001-2002. Preburn inventory was conducted in 2002-2003. Slash piles were removed from the site by means of chipping and selected pile burns in the fall of 2003. The prescribed burn of the treatment units was conducted in September and October 2004. The first year of post-burn monitoring was completed in the summer and fall of 2005.

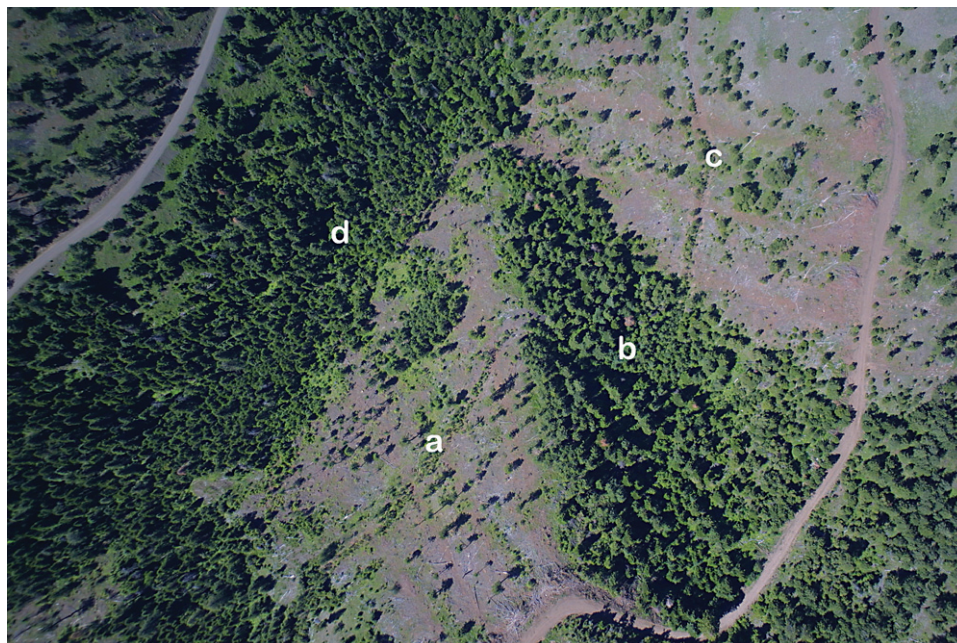


Figure 4—Aerial view of treatments at mid-elevation within the Lick Creek Demonstration Site showing fuels yarding (a, c) on a wildlife leave unit (b) above Lick Creek (d). Permanent monitoring plots are distributed near the center of each unit from top to bottom.

Table 1—Replicate (3) treatments implemented on the Lick Creek Demonstration Site, Blue Mountains, Pomeroy Ranger District, Umatilla National Forest.

Treatment	Description
Control	No harvest, no prescribed burn - stand left in original state.
Prescribed burn only	No harvest, prescribed burn of stand in its original state.
Commercial yarding - prescribed burn	All trees unmarked as leave trees that were 6 inches d.b.h. or greater that had a minimum 8 foot long piece to a 3 inch top were cut and removed to the landings, whole tree yarding was not required but generally done to improve efficiency of operation; post-harvest prescribed burn was applied. Objective of treatment was to leave a greater quantity of fuel in place on the units.
Fuels yarding - prescribed burn	All trees unmarked as leave trees that were 3 inches d.b.h. or greater that had a minimum 8 foot long piece to a 3 inch top were cut and removed to the landings; whole tree yarding was required; down material meeting the cutting specifications for commercial yarding (6+ inches d.b.h.) were cut and yarded; post-harvest prescribed burn was applied. Objective of treatment was to minimize fuel accumulations on the units.

Harvest

A total of 85 acres of the site were harvested in a 40-day period, commencing in mid December 2001. Winter logging in the Blue Mountains is at risk of being stopped at any time because of severe storm conditions and snow accumulation. Fortunately, severe weather conditions never developed until after the harvest had been completed in late January, 2002, allowing harvest to proceed with minimal snow cover.

Yarding was conducted for 74% of the harvest area with gravity feed skyline system utilizing a skyline yarder and a motorized support carriage. Ground-based yarding with a tracked skidder was conducted over the remaining 26% of the harvest area. Whole tree yarding was required as part of the treatment prescription to minimize fuel loading on the site.

A stationary, pull-through, motorized, radio-controlled delimber was used to process the whole trees that were yarded to the landing. After delimbing, the trees were sorted according to merchantable (sawlog) or unmerchantable (tonwood, fiber wood), cut to specified lengths, and piled into decks for loading. One-hundred loads were hauled from the site—51 sawlog loads, 33 tonwood loads, and 16 fiber loads.

The total yield of the harvest averaged 27.14 tons per acre for the 85-acre harvest area of the Lick Creek Site. Yield was portioned as follows - sawlog (1171 t, ~ 194 gross mbf), tonwood (761 t), fiber wood (374 t).

Chipping for Biomass Fuel

Whole tree removal from the harvest site meant that large slash piles accumulated at the landings at the top of each unit. These piles were large, ranging from 1.41 tons/acre to 4.67 tons/acre and were considered a hazard to the conduct of the prescribed burn because of their location and potential to initiate escape fire. Removal of the piles proceeded in the late fall of 2003 through a service contract to a local contractor to chip the slash for sale as biomass fuel. Because of limited road access, the chipper was stationed at a site that provided access to haul trucks. Slash from the piles was transported by trucks to the chipper for processing. Slippage of some slash piles down the steep slopes of the site made some of the slash inaccessible to loaders. This material was pile burned after the slash chipping had been completed. A total of 33 piles yielded 482.44 dry t of chipped wood for sale as biomass fuel.

Prescribed Burn

The burn was conducted from in a 5-day period from September 30-October 4, 2004. The burn prescription targeted reduction of fuels and understory fire-intolerant and shade-tolerant tree species on the site as the principal objectives. The principal Ignition pattern was strip head-fire over most of the site with backing fire used through heavy fuel accumulations and down very steep slopes. Flame-lengths were to be kept under 4 ft to limit fire intensity. Seven burn units are designated, combining treatment units to facilitate control and consistency in the character of the burn. Ignitions started at highest points of the site and progressed down-slope and to lower elevations within the site over the burn period. Surface fuels were typically a mosaic of grass and woody fuel patches, intermixed with live shrub and tree materials. The small live tree component was especially significant in the higher elevation units. The live shrub component was most significant in the lower elevation and environmentally warmer units. Woody fuel loading varies across the Lick Creek site according to treatment. The highest woody

fuel loadings were in the commercial yarding units harvest with fuelbeds in the Fire Behavior Fuel Model 10 and 11 categories depending on the mix of herbaceous and live fuels and amount of overstory.

At the beginning of the burn period, temperatures (55-62 ° F) and relative humidity (38-44%) were near the lower limit of the burn prescription providing an advantage in keeping fire intensity low while still accomplishing the prescription objectives. Backing fires were ineffective under these conditions, so strip head-fire ignition was the principal means of ignition. Temperatures climbed into the low 70's and humidity dropped into the high 20's by the end of the 5-day burn period and back-firing became the principal means of fire spread. Winds occurred in the typical fall convective wind pattern and were not a factor at anytime during the burn period.

Initial estimates indicate that an average reduction of 80% was achieved in the woody fuel and ground fuel loading over the Lick Creek site.

Monitoring System

Five permanent plots are distributed within each treatment unit near the center from the top to the bottom of the unit (Fig. 4). The plots were inventoried pre- and post-burn. Pre-harvest plots were sampled in the same locality as the permanent plots but do not represent the exact location of the permanent plots. The plot is circular with a diameter of 50 m. The center of the plot is the photo point from which a radial sequence of photos is taken of the entire perimeter of the plot. Two 25-m transects from the plot center along the contour of the slope are used to collect point and microplot data for the following overstory and understory attributes: fuel loading, species composition and canopy coverage, tree density by diameter class and species, stand canopy stratification, height, and composition, and soil surface coverage and composition. A series of digital photos are taken of 1-m² microplots along each transect. The data is being entered and summarized in FIREMON (2006).

Summary of Preliminary Findings

Stand structure was significantly altered by harvest with reductions of overstory canopy coverage by as much as 70% in some treatments. The majority of the dominant mid-story canopy layer was eliminated by the harvest. However, a substantial amount of the understory tree layer of short and less than 3 inches d.b.h. remained intact after harvest. The prescribed burn damaged the majority of the understory layer but the full extent of the mortality was not fully expressed in the 2005 inventory. Herbage production increased dramatically in areas of moderate fire intensity but did not show a similar response in areas of high fire intensity. Less than 1% mortality was evident in 2005 in the leave tree populations across all of the harvest treatment units. A low degree of mortality is evident in the overstory of the burn only treatments but the condition of many of the trees suggest that greater levels of mortality are to be expected in coming years. Fuels reduction varied greatly among treatment replications with the most uniformity reduction in the commercial yarding treatments and the greatest variation in the burn only treatments. Contractor revenue profits from the harvest and biomass fuel were modest and dependent on the provision of service contracts by the USFS Pomeroy Ranger District in addition to the release of the products to the contractors for independent sale.

Project Sponsors

Funding to initiate the development of the Lick Creek Demonstration Site was provided by the Joint Fire Science Program, USFS Umatilla National Forest, Washington State University, Rocky Mountain Elk Foundation, Blue Mountain Elk Initiative, and Guy Bennett Lumber Company.

Literature Cited

- Agee, J.K. 1996. Critical stand characters for crown-fire-safe forests. pp. 52-68. In: Proc. 17th Annual Forest Vegetation Management Conference, Redding CA, Jan 16-18, 1996.
- Applegate V., Dupuis V., Ablutz M., Klinkhammer S., Slaughter S., Yelczyn B., Becker R. 1997. Use of habitat types and fire regimes in landscape assessments and stand level prescriptions. pp. 36-72. In: Forest Management Into the Next Century: What Will Make It Work? Proceedings. Spokane WA: Forest Products Society and USDA For Serv.
- Baumgartner D., Johnson R.L., DePuit E.J. 2002. Small diameter timber resource management, manufacturing, and markets. Proc. of Conf. held Feb. 25-27, 2002, Spokane WA. Pullman WA: WSU Extension MISC 0509.
- Bott K. 1998. Silvicultural prescriptions—Lick Analysis Area. Staffing paper, Lick Analysis File, Pomeroy Ranger District, Umatilla National Forest, USDA Forest Service, Pomeroy, WA.
- FIREMON. 2006. Fire effects monitoring and inventory system. Online: <http://firemon.org>.
- Fujishin M. 1998. Environmental assessment for the Lick timber sale and fire reintroduction project. Staffing paper, Lick Analysis File, Pomeroy WA: Pomeroy District, Umatilla National Forest, USDA For. Serv.
- Graham R.T., Harvey A.E., Jain T.B., Tonn J.R. 1999. Effects of thinning and similar stand treatments on fire behavior in western forests. General Technical Report PNW-GTR-463. Portland, OR: USDA For. Serv., PNW For and Range Exp. Sta.
- Hille M.G., Stephens S.L. 2003. Mixed conifer forest duff consumption during prescribed fires: tree crown impacts. For. Sci. 51:417-424.
- Johnson L. 1997. Overview of timber harvesting technology and costs. pp. 89-94. In: Forest Management Into the Next Century: What Will Make It Work? Conference proceedings sponsored by the Forest Products Society and USDA Forest Service, Spokane, WA, November 19-21, 1997.
- Johnson C.G. Jr., Clausnitzer R.R. 1992. Plant associations of the Blue and Ochoco Mountains. USDA, For. Serv., PNW Region, Wallow-Whitman National Forest, R6-ERW-TP-036-92.
- Lorentz S. 1997. Vegetative conditions in the Lick Prescribed Fire Project Area. Staffing paper, Lick Analysis File, Pomeroy, WA: Pomeroy District, Umatilla National Forest, USDA Forest Service.
- Martin M. 1998. Report on the fire and fuels management issues in the Lick Analysis Area. Staffing paper, Lick Analysis File, Pomeroy, WA: Pomeroy District, Umatilla National Forest, USDA Forest Service.
- Maruoka K.R. 1993. A fire history survey in selected *Pseudotsuga menziesii* and *Abies grandis* stands in the Blue Mountains of Oregon and Washington. Pomeroy, WA: Pomeroy District, Umatilla National Forest, USDA Forest Service.
- Ryan KC, Frandsen W.H. 1992. Basal Injury From Smoldering Fires in Mature *Pinus ponderosa* Laws. International Journal of Wildland Fire 1(2):107-118.

- Stephens S.L., Finney M.A. 2001. Prescribed fire mortality of Sierra Nevada mixed conifer tree species: effects of crown damage and forest floor combustion. *Forest Ecology and Management* 162: 261-271.
- Stokes B.J., Klepac J.F. 1997. Ecological technologies for small-diameter tree harvesting. pp. 95-101. In: *Forest Management Into the Next Century: What Will Make It Work?* Conference proceedings sponsored by the Forest Products Society and USDA Forest Service, Spokane, WA, November 19-21, 1997.
- Thies W.G., Westlind D.J., Loewen M., Brenner G. 2006. Prediction of delayed mortality of fire-damaged ponderosa pine following prescribed fires in Eastern Oregon, USA. *International Journal of Wildland Fire* 15: 19-29.
- Wagner F.G., Keegan III, C.E., Fight R.D., Willits S. 1997. Potential for small-diameter saw timber utilization by the current industry infrastructure in Western North America. pp. 115-120. In: *Forest Management Into the Next Century: What Will Make It Work?* Proceedings. Spokane WA: Forest Products Soc. and USDA Forest Service.
- Wickman B.E. 1992. Forest health in the Blue Mountains: The influence of insect and disease. Gen. Tech. Rep. PNW-GTR-295. Portland, OR: USDA Forest Service, Pacific Northwest Forest and Range Experiment Station.
- Williams J.T., Schmidt R.G., Norum R.A., Omi P.N., Lee R.G. 1993. Fire related considerations and strategies in support of ecosystem management. Staffing paper, Fire and Aviation Management, Washington Office, USDA Forest Service.

Response of Fuelbed Characteristics to Restoration Treatments in Piñon-Juniper-Encroached Shrublands on the Shivwits Plateau, Arizona

Helen Y. Smith¹, Sharon Hood², Matt Brooks³, J.R. Matchett⁴, and Curt Deuser⁵

Abstract—The recent encroachment of piñon (*Pinus edulis*) and juniper trees (*Juniperus osteosperma*) into historically shrub- and grass-dominated landscapes has caused major changes in ecosystem structure and function, including dramatic changes in fuel structure and fire regimes. Such encroachment is currently occurring on thousands of acres on the Shivwits Plateau in northwestern Arizona and land managers are seeking effective techniques to restore these areas to pre-invasion conditions and reduce the threat of high severity crown fires. A study was established on the Shivwits Plateau to test the effectiveness of three thinning techniques for reducing the density of recently established piñon and juniper trees and to assess changes to the fuelbed structure. The thinning treatments were: (1) cut and leave; (2) cut, buck and scatter; and (3) herbicide. The line-point intercept method was used to characterize changes in the fuelbed structure. Belt transects were used to quantify tree density. Responses of the shrubs and suffrutescent plants (herein collectively referred to as 'shrubs') are reported. Generally, there was more live shrub cover in the treatment units versus the control units. In addition, the mechanical treatments added woody fuels to the initially sparse sites. These two structural changes are expected to help to carry surface fire through the treated areas.

Introduction

Tausch and others (1981) found evidence of expansion both in tree densities and geographical distribution of piñon-juniper (*Pinus* spp.- *Juniperus* spp.) woodlands over the last 175 years. The type conversion from shrubland to woodland leads to a decrease in understory plants such as shrubs, suffrutescent plants, bunchgrasses, and herbaceous species as the overstory canopy closes. This woodland expansion is a major concern for land managers due to the resulting loss of wildlife habitat associated with sagebrush steppe, decreased species diversity, loss of soil seedbanks, decreased aquifer recharge, increased soil erosion, and increased intensity of wildfires (Koniak and Everett 1982, Wilcox and Breshears 1994, Davenport and others 1998, West 1999, Miller and others 2000).

The range expansion of piñon and juniper is associated with increased fire return intervals due in large part to fire suppression and the reduction of surface fuels caused by the introduction of livestock grazing by European settlers (Miller and Rose 1999). In an attempt to return stands to pre settlement

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

¹ Ecologist, USFS, Rocky Mountain Research Station, Fire Sciences Lab, Missoula, MT. hsmith04@fs.fed.us

² Forester, USFS, Rocky Mountain Research Station, Fire Sciences Lab, Missoula, MT.

³ Research botanist USGS, Western Ecological Research Center, Las Vegas Field Station, Henderson, NV.

⁴ Biologist, USGS, Western Ecological Research Center, Las Vegas Field Station, Henderson, NV.

⁵ Supervisory restoration biologist, NPS, Lake Mead National Recreation Area, Boulder City, NV.

conditions dominated by sagebrush steppe and shorter fire return intervals and to improve livestock forage and wildlife habitat, land managers have attempted to reintroduce fire and manipulate fuel conditions using mechanical, chemical, and seeding treatments.

Where woodlands are dense, shading inhibits herbaceous development, limiting the surface fuels necessary to support a low intensity surface fire. In this situation, fire does not propagate easily except under extreme fire weather conditions which typically results in undesirable intense overstory crown fires (Miller and others 2000). Where woodlands are more open and surface fuels still exist, managers can create low to moderate intensity surface fires with sporadic torching of larger trees, but even in these conditions fire can be difficult to propagate. For these reasons, sites have often been prepared before burning, typically by chaining landscapes to uproot trees and provide opportunities for early successional forbs, grasses, and shrubs to re-establish. However, chaining results in removal of both pre and post settlement trees and creates significant soil disturbance, which is not compatible with the management goals of many land management agencies, especially the National Park Service. As a result, mechanical thinning or chemical treatment of post settlement trees is becoming more common since such treatments create uneven-aged woodland stands which better represent historic conditions, provide better wildlife habitat, and do not create significant soil disturbance. Minimizing soil disturbance is especially important in areas where cultural resources may otherwise be at risk. By reducing overstory canopy cover, understory plants will have a chance to grow, increase cover, and create fine fuels that will support a lower intensity surface fire through the area.

To this end, this study on the Shivwits Plateau in northwestern Arizona was established to compare the effectiveness of two types of mechanical and one type of chemical thinning treatments as well as their costs for:

1. reducing densities of post-settlement piñon (*Pinus edulis*) and juniper (*Juniperus osteosperma*) trees;
2. increasing cover and seedbank density of native annual plants and perennial grasses;
3. increasing plant species diversity;
4. minimizing cover and seedbank density of invasive alien plants; and
5. creating a fuelbed that promotes the re-establishment of historic low to moderate intensity surface fires.

This report examines the first and fifth objectives.

Materials and Methods

Study Site

The study site (~405 ha/1,000 ac) is located within a single watershed on the northern rim of the Grand Canyon on the western Colorado plateau. The administrative boundaries of the project are within the National Park Service (NPS) portion of the Grand Canyon-Parashant National Monument, an area jointly managed with the Bureau of Land Management (BLM), Arizona Strip Field Office. The site is at 1,890 m (6,200 ft), with slopes from two to 15 percent. Mean annual precipitation is 33 to 43 cm (13 to 17 inches), bimodally distributed in summer monsoons from late June to early September, and winter frontal systems from November through March. Mean annual soil temperature is 9 to 13 °C (49 to 56 °F), and the frost-free period is 135 to 150 days.

European settlement of the area occurred in the mid 1800s and included extensive cattle grazing until the late 1980s when grazing was terminated on the site. Historic evidence of prolific cattle grazing remains in the study region including corrals, drift fences and earthen water tanks. Some of this region was chained in the late 1950s to early 1960s by a local rancher in an effort to improve range forage conditions. The area was “withdrawn land” by the Bureau of Reclamation in the 1930s and was transferred to the National Park Service in 1964.

Fire suppression has likely occurred concomitantly with European settlement. Organized fire fighting responsibilities have been shared by the BLM and NPS since the 1950s. A Prescribed Natural Fire Plan was implemented for the area in 1998 and fires are currently being managed as “wildland fire use” which is synonymous with allowing lightning-ignited fires to burn under certain management approved conditions.

Lightning storms commonly occur in the area throughout the monsoon season. There is evidence that moderately-sized fires burned historically in the area [up to 40 ha (100 ac)], but in the last 25 years smaller fires less than one hectare and single tree fires were more common. In an attempt to reintroduce low- to moderate-intensity surface fires, the NPS has implemented over 2,400 ha (6,000 ac) of prescribed fires in the area since the program started in 1994. Prescribed burn objectives were only met on approximately 600 ha (1,500 ac), which included the majority of the formerly chained areas. Most of the untreated/unchained areas did not carry fire with the use of a helitorch except under extreme fire weather conditions. Monitoring has shown that plant diversity has generally increased in burned areas; however, native grasses have only increased in small isolated areas, possibly due to a depleted soil seedbank. In order to help meet resource objectives, assessment of alternative treatments besides simply attempting to reintroduce fire appears to be necessary.

Current land management goals at this site are to preserve, restore, and maintain naturally functioning ecosystems and cultural resources. Other goals are to maximize native plant and animal diversity within the natural range of variation. Primary management concerns are related to soil erosion potential, and it is believed that current site conditions will not adequately sustain soil resources in the event of a high severity crown fire. The site is ideal to conduct restoration activities since cattle grazing has been excluded; no elk exist in the area; and deer, small mammals, and insects are the only remaining grazers. The lack of excessive grazing pressure should facilitate the re-establishment of native grasses, forbs, shrubs, and suffrutescent plants. The NPS Lake Mead Exotic Plant Management Team is available to control invasive plants in the event that they begin to appear in the study area.

Study Design

Thirty-two, 8.1 ha (20 ac) units were laid out and each unit was randomly assigned to be left untreated (control) or to have one of three thinning treatments applied. The treatments consisted of two types of mechanical and one chemical thinning treatment. The goal of all thinning treatments was an 80 percent reduction of post settlement trees. Land managers estimated that this level of tree reduction would open the stands enough to provide favorable establishment and growing conditions for perennial grasses and other vegetation, provide fuels to support a low to moderate intensity surface fire, and provide enough ground cover to reduce the potential for soil erosion. Post settlement trees were defined as those ranging in age from 1 to 175 years

old (Class 1 to 3 trees; Bradshaw and Reveal 1943). None of the oldest trees (Class 4) were to be cut or sprayed. This classification of piñon and juniper trees was based on general guidelines such as diameter at stump height or breast height, tree height, and growth form.

The mechanical thinning options consisted of either a cut-leave or a cut-buck-scatter scenario. Trees were not marked prior to cutting, but rather the thinning crews were briefed on what factors constitute a post settlement tree and were given the direction to cut four post settlement trees and leave the fifth post settlement tree they encountered uncut. In this manner, an 80 percent reduction in tree density of each species should occur. In the cut-leave treatment, trees were cut with either loping shears or chainsaws and left where they fell. The cutting methods were the same in the cut-buck-scatter treatment, but the larger trees were then limbed to manageable lengths and the material scattered across the site, avoiding placing slash under the drip-lines of uncut trees. Approximately 20 percent of the mechanical thinning was accomplished by a National Park Service fire crew with the remainder completed by contract crews.

The herbicide thinning treatment used 15 percent Tordon 22K (DOW) that was batch mixed at 11.4 liters (three gallons) increments directly into SP-3 backpack sprayers at a rate of 709.8 milliliters (24 fluid ounces) of chemical to 3.78 liters (1 gallon) of water with 29.6 milliliters (one fluid ounce) of Blaze-on blue dye and one milliliter (0.03 fluid ounce) of kinetic nonionic surfactant. Since this method is a spot treatment, the rate applied per unit area is dependent upon the target tree density. For this treatment, the average application was 1.84 liters per hectare (25.15 ounces per acre) of Tordon 22K. The spray mixture was applied as a solid stream to the base of the tree at the soil interface (Williamson and Parker 1996). A 4.6 m (15 ft) buffer was left around each pre settlement tree encountered due to concerns for chemical drift in the soil. Other trees, regardless of their classification that fell in this zone, were not treated. It was estimated that these trees would constitute the 20 percent residual leave tree target; therefore, every post-settlement tree located outside the buffer zones was treated with herbicide. Herbicide application was performed by the Exotic Plant Management Team from Lake Mead Recreation Area.

No cutting or herbicide application was implemented in the control units. All treatments were completed prior to the start of our sampling.

Sampling

In each treatment unit, three plots were randomly located. At each plot, we laid out a 50 m (164 ft) line transect, which ran down the center of a 6x50 m (20x164 ft) belt transect. Vegetation data was collected along the 50 m line transect using the line-point intercept method (Lutes and others 2006) and tree data was collected within the belt transect. Plots were established in 2004 after completion of the thinning treatments and measured in late August/early September of 2004 and 2005.

Trees—Since cutting took place before plot establishment, we could not note the features such as tree height, growth form, or diameter at breast height or stump height of cut trees that Bradshaw and Reveal (1943) used for their classification system and that the thinning crew used when making the decision of which trees to cut. We used data from Miller and others (1981) to develop relationships between diameter at stump height, diameter at breast height, and groundline diameter (g.l.d.) and we assigned each of

the trees/stumps in our data set a Class based solely on g.l.d. (table 1). Trees that were treated with herbicide were either labeled as dead or “sick.” If, by appearance, they were unhealthy and expected to die in the near future they were deemed sick.

All trees/stumps located within the 6x50 m belt transect that had a g.l.d. of 7.6 cm (3 inches) or greater were recorded along with the species. This left the smallest Class 1 trees unmeasured, leading to the assumption that the Class 1 trees measured and those that were thinned were representative of smaller trees as well. Although other tree attributes were measured, density and percent reduction will be the only tree data presented in this paper.

Surface fuels—Along the 50 m (164 ft) line transect that bisected the belt transect, we sampled fuel groups by category (fine slash, coarse slash, fine woody debris, coarse woody debris, grass, live shrubs, dead shrubs, trees by species, forbs, and bare soil) using the line-point intercept sampling methods. The height of the tallest interception by fuel group was recorded at 0.5 m (1.6 ft) intervals. Since we did not sample prior to treatment establishment, the distinction between ‘slash’ and ‘debris’ was made in an attempt to determine woody fuel presence prior to and following treatment application. True shrubs such as scrub oak (*Quercus turbinella*), cliffrose (*Purshia mexicana*) and sagebrush (*Artemisia tridentate*) as well as suffrutescent plants such as broom snakeweed (*Gutierrezia sarothrae*) are combined in our ‘live shrub’ and ‘dead shrub’ categories. The fuel that will contribute to fire spread in this system is made up of plants such as shrubs and grasses as much as it is woody fuels; therefore, much of our focus was spent on assessing continuity of plant growth. Live shrub cover is the only surface fuel component that will be presented in this paper.

Data Analysis

For the line-point intercept method of cover determination, percent cover is calculated by summing the number of hits per line and dividing by 100. In our situation, we had 100 points per line, so it was a matter of simply summing the number of hits. For example, if forbs were encountered at 13 of the 100 points along a line, this computes to a 13 percent cover for forbs.

Table 1—Groundline diameter classes used to distinguish tree class for juniper and piñon trees. Breakpoint diameters based on Bradshaw and Reveal (1943) and Miller and others (1981).

	Diameter at groundline			
	Juniper		Piñon	
	-- cm --	-- in --	-- cm --	-- in --
Class 1	<10.2	<4	<8.9	<3.5
Class 2	10.2-24.1	4-9.5	8.9-21.8	3.5-8.6
Class 3	24.2-35.8	9.6-14.1	21.9-31.8	8.7-12.5
Class 4	>35.8	>14.1	>31.8	>12.5

We used general linear mixed models (GLMM) to examine differences in live shrub cover and pre treatment tree density between treatments (SAS Institute v.9.1, Littell and others 1996). All mixed models used a completely randomized design with subsampling and the Tukey-Kramer method to detect treatment differences.

Results

Live Tree Density

Prior to treatment, there were no statistical differences in density of either juniper ($F_{3,26} = 0.28$; $p = 0.84$) or piñon ($F_{3,26} = 0.65$; $p = 0.59$) between treatment types. Across all treatment units, there was an average of 508 juniper trees per hectare (t.p.h.) [206 trees per acre (t.p.a.)] and an average of 134 piñon t.p.h. (54 t.p.a.).

The cut-leave treatment reduced post settlement juniper trees by 83 percent and piñon by 77 percent. Of the pre settlement trees identified by our definition, 11 percent of the juniper and no piñon trees were cut (table 2).

Ninety-two percent of the post settlement juniper trees were cut in the cut-buck-scatter treatment, with 100 percent Class 1 juniper trees cut and 99 percent of Class 2 trees cut. Seven percent of the pre settlement juniper trees were also cut. Of the post settlement piñon trees identified, 64 percent were cut. None of the pre settlement piñon trees were cut (table 2).

Of the herbicide-treated juniper trees, 50 percent of the post settlement trees were dead three years after application with another 18 percent designated as sick. Providing these trees die as a result of the treatment, the juniper trees will be reduced by 68 percent. Thirty-two percent of the pre settlement juniper trees were killed and another 11 percent were sick. Seventy percent of the post settlement piñon trees were dead in 2005 and seven percent were sick. Combined, this will result in a 77 percent reduction in post settlement piñon trees. There was only one pre settlement piñon tree identified and it was killed (table 2).

Table 2—Percent reductions of trees by treatment, species, and tree class. For the herbicide treatment, percent reductions based on dead as well as dead plus sick are included.

Treatment	Species	Class 1		Class 2		Class 3		Total Post Settlement		Class 4 (Pre Settlement)	
----- Percent reduction -----											
Cut-Leave	juniper	93		86		69		83		11	
	piñon	82		84		25		77		0	
Cut-Buck-Scatter	juniper	100		99		69		92		7	
	piñon	89		65		18		64		0	
----- Percent reduction -----											
		dead	dead + sick	dead	dead + sick	dead	dead + sick	dead	dead + sick	dead	dead + sick
----- Percent reduction -----											
Herbicide	juniper	53	73	49	64	49	75	50	68	32	43
	piñon	95	95	69	77	27	45	70	77	100	na

Live Shrub Cover

There were no significant differences in live shrub cover in 2004 ($F_{3,26} = 0.19$; $p > 0.9$) (fig. 1). Cover in the areas treated with herbicide was highest with 5.5 percent cover. The cut-leave treatment had the lowest cover with 3.8 percent. Intermediate between the herbicide and cut-leave treatments were the cut-buck-scatter and control treatments, with 4.3 and 5.1 percent cover, respectively.

Cover increased in all treatments in 2005. Control units had 15 percent cover, cut-buck-scatter units had 27 percent cover, cut-leave units had 38 percent cover, and herbicide units had 36 percent cover. There were statistical differences in live shrub cover between treatments ($F_{3,26} = 12.29$; $p < 0.0001$). Live shrub cover in the control units was significantly lower than the thinned treatments ($p < 0.05$); however, there were no differences between the thinned treatments (fig. 1).

Discussion

Live Tree Density

By only providing general growth form guidelines to the cutting crew, it most likely cost less per unit area to execute the treatments, but it also left more ambiguity and room for failure in meeting the treatment objective of 80 percent reduction in post settlement tree density. Depending on land management goals, the range of reduction in post settlement tree density that we captured

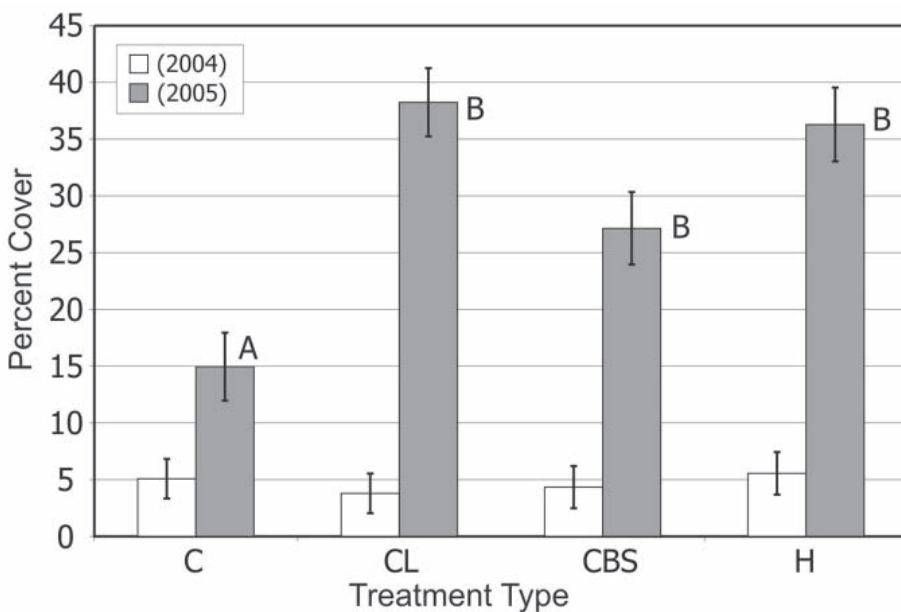


Figure 1—Percent live shrub cover for 2004 and 2005 by treatment type as measured using the line-point intercept method. There were no significant differences between types in 2004 ($F_{3,26} = 0.19$; $p = 0.9033$). Uppercase letters (A, B) represent significant differences between types in 2005 ($F_{3,26} = 12.29$; $p < 0.0001$). C = control; CL = cut-leave; CBS = cut-buck-scatter; and H = herbicide. Error bars represent one standard error about the mean.

(64 to 92 percent) may be acceptable. In addition, if pre settlement tree retention is only of low to moderate priority, then this method of determination for thinning is probably appropriate. If the goal of an 80 percent reduction in post settlement trees is an important target and retaining pre settlement trees is a high priority, it may well be worth the cost of better assessing tree ages by coring the largest trees and marking trees to be thinned or retained. Another option may be to thin trees based on a target tree density, rather than a percent reduction of a portion of current density based on tree diameter.

Based on our methods of assessment, it appears that the cut-leave thinning treatment produced results closest to the objective of 80 percent tree reduction (table 2). This may well be due to the relatively simple nature of this method. A cut tree provides an immediate measure by which to assess efficacy and, by not taking time to buck and scatter the larger trees, a more consistent flow can be kept by the thinning crew. Cutting was heavier in the smaller trees (Classes 1 and 2) in both of the cutting treatments, which may be an indication of the level of uncertainty in using general growth form as a cutting guideline.

The intricacies of the herbicide application, with care taken for soil drift, may have led to the low reductions in post settlement trees that we documented. Another consideration may be that crews were constrained by maximum allowable herbicide application per unit area.

Live Shrub Cover

Live shrubs responded favorably to the thinning treatments. In 2004, live shrub cover was second highest in the control units at 5.1 percent. In 2005, following a strong monsoon season, the cover of live shrubs in the control units nearly tripled to 15 percent. This threefold increase, however, was the lowest in 2005 and was dwarfed by the response seen in the treatment units. The cut-leave units underwent the greatest increase in live shrub cover with a tenfold increase, but were not distinguishable from the other thinned treatments. Live shrub cover in the cut-buck-scatter and herbicide units increased by roughly six times (fig. 1). Observationally, most of the increase in shrub cover came from broom snakeweed (*Gutierrezia sarothrae*); a suffrutescent plant which is an increaser on disturbed sites (U.S. Department of Agriculture, Forest Service 1937) and can help minimize soil erosion (Campbell and Bomberger 1934).

In summary, regardless of the accuracy of the thinning treatments relative to the goal of 80 percent post settlement tree reduction, thinning is apparently facilitating the creation of a fuelbed which should help to carry a surface fire through the area. The thinning treatments have opened the sites up, allowing an increase in live shrub cover as well as adding woody structure that should help to support a desirable surface fire and provide nurse sites for future plant germination and establishment. Dependant on funding, the next phase of this study will be to burn half of the units to determine the impacts of the thinning treatments on fire behavior and consequent fire effects.

Acknowledgments

We would like to thank the Joint Fire Sciences for funding this study (#03-3-3-58) and Duncan Lutes (SEM; Missoula, MT) for helping to develop our methods. In addition, Duncan Lutes and Mick Harrington of the Missoula Fire Lab greatly improved this paper with their reviews. Logistics support from Shirley Kodele, NPS and Tim Duck, BLM in St. George, UT has been invaluable.

References

- Bradshaw, K. E.; Reveal, J. L. 1943. Tree classification of *Pinus monophylla* and *Juniperus utahensis*. *Journal of Forestry*:100-104.
- Campbell, R. S.; Bomberger, E. H. 1934. The occurrence of *Gutierrezia sarothrae* on *Bouteloua eriopoda* ranges in southern New Mexico. *Ecology*. 15(1): 49-61.
- Davenport, D. W.; Breshears, D. D.; Wilcox, B. P.; Allen, C. D. 1998. Viewpoint – sustainability of piñon-juniper ecosystems – a unifying perspective of soil erosion thresholds. *Journal of Range Management*. 51:229-238.
- Koniak, S.; Everett, R. L. 1982. Seed reserves in soils of successional stages of piñon woodlands. *The American Midland Naturalist*. 108:295-303.
- Littell, R. C.; Milliken, G. A.; Stroup, W. W.; Wolfinger, R. D. 1996. SAS system for mixed models. SAS Institute, Cary, N.C.
- Lutes, D. C.; Keane, R.E.; Caratti, J. F.; Key, C. H.; Benson, N. C.; Sutherland, S.; Gangi, L. J. 2006. FIREMON: Fire effects monitoring and inventory system. General Technical Report RMRS-GTR-164-CD, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO USA.
- Miller, E. L.; Meeuwig, R. O.; Budy, J. D. 1981. Biomass of Singleleaf Pinion and Utah Juniper. INT-RP-273, U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 18 p.
- Miller, R. F.; Rose, J. A. 1999. Fire history and western juniper encroachment in sagebrush steppe. *Journal of Range Management*. 52:550-559.
- Miller, R. F.; Svejcar, T. J.; Rose, J. A. 2000. Impacts of western juniper on plant community composition and structure. *Journal of Range Management*. 53:574-585.
- Tausch, R. J.; West, N. E.; Nabi, A. A. 1981. Tree age and dominance patterns in Great Basin pinyon-juniper woodlands. *Journal of Range Management*. 34(4): 259-264.
- U.S. Department of Agriculture, Forest Service. 1937. Range Plant Handbook. Washington, D.C. 532 p.
- West, N. E. 1999. Juniper-pinyon savannas and woodlands of western North America. Pp. 288-308 in Anderson, R. C.; Fralish, J. S.; Baskin, J. M. (eds.) *Savannas, barrens, and rock outcrop plant communities of North America*. Cambridge University Press, London UK.
- Wilcox, B. P.; Breshears, D. D. 1994. Hydrology and ecology of piñon-juniper woodlands: conceptual framework and field studies. Pp. 109-119 in Shaw, D. W.; Aldon, E. F.; LoSapio, C. (eds.) *Proceedings: desired future conditions for piñon-juniper ecosystems*. GTR-RM-258, US Department of Agriculture, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- Williamson, M.; Parker, D. April 1996. Low-Impact, Selective Herbicide Application For Control of Pinon/Juniper: A Field Guide. USDA, Forest Service, Southwestern Region.

Effect of a Spaced Thinning in Mature Lodgepole Pine on Within-Stand Microclimate and Fine Fuel Moisture Content

R. J. Whitehead¹, G. L. Russo¹, B. C. Hawkes², S. W. Taylor²,
B. N. Brown³, H. J. Barclay⁴, and R. A. Benton⁵

Abstract—Thinning mature forest stands to wide spacing is prescribed to reduce crown bulk density and likelihood of severe crown fire behaviour. However, it may adversely affect surface fuel load, moisture content and within-stand wind, which influence surface fire behaviour and crowning potential. Comparison of a mature lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) stand in southeastern British Columbia to an adjacent stand with half the basal area removed by thinning to 4 m inter-tree spacing found a decrease in canopy interception of rainfall and increases in solar radiation, windspeed, and near-surface air temperature during peak fire danger hours over 13 fire seasons. Moisture content of needle litter and fuel moisture sticks was measured in both stands in 2005. Between-treatment differences in moisture content of sticks and litter were greatest after rain, but decreased quickly as fuels dried, to very small at moderate fire danger. Prediction of moisture content of lodgepole pine needle litter using the Canadian Fire Weather Index System also improved as fuels dried and worked well for both stands at moderate fire danger. There was only one day at higher fire danger during the study. Further studies should examine physical models of fuel moisture and microclimate under a wider range of stand densities, fuel types and climatic conditions.

Introduction

Thinning mature forest stands to a wide inter-tree spacing is sometimes prescribed to reduce crown bulk density and lower the likelihood of severe crown fire behaviour (Hirsch and Pengelly 1999). However, thinning may also affect surface fuel loading, fine fuel moisture content and within-stand winds, which in turn affect surface fire behaviour and crowning potential (Rothermel 1983; Scott 1998; Scott and Reinhardt 2001). Rates of wetting or drying, and consequently moisture content, of fine surface fuels are influenced by microclimatic factors that are expected to change when a stand is thinned. These factors include canopy interception of rainfall and solar radiation, and near surface air temperature, relative humidity and within-stand windspeed (Rothermel 1983; Forestry Canada 1992).

The purpose of this paper is to compare and contrast a natural mature lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) stand to an adjacent stand which was thinned to uniform 4 m spacing in February 1993, with respect to:

- within-stand microclimate parameters that are likely to affect moisture content of fine surface fuels;

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

¹ Research Silviculturists, Natural Resources Canada, Canadian Forest Service, Victoria, British Columbia, Canada. rwhitehe@nrncan.gc.ca

² Fire Research Officers, Natural Resources Canada, Canadian Forest Service, Victoria, British Columbia, Canada.

³ Senior Research Technician, Natural Resources Canada, Canadian Forest Service, Victoria, British Columbia, Canada.

⁴ Research Scientist—Modeling, Natural Resources Canada, Canadian Forest Service, Victoria, British Columbia, Canada.

⁵ Forest Meteorologist, Natural Resources Canada, Canadian Forest Service, Victoria, British Columbia, Canada.

- measured moisture content of fine surface fuels; and,
- difference between actual moisture content of lodgepole pine needle litter and values predicted by the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987).

Study Area

This study was conducted at one of three sites where, since 1992, researchers from the Canadian Forest Service and Forest Engineering Research Institute of Canada and operations staff from the British Columbia Ministry of Forests and Range have studied the efficacy of commercial thinning to uniform wide spacing for reaching several stand-level management objectives in natural 70 to 100 year old lodgepole pine.

The site is located south of Cranbrook in south-eastern British Columbia at 49° 25' N, 115° 36' W, on level terrain in a broad valley at 1350 m elevation. The overstorey consists of a single cohort lodgepole pine stand that originated after wildfire in 1912, with a few scattered western larch (*Larix occidentalis* Nutt.) trees of about the same age.

In 1992, one of three adjacent 15 to 20 ha treatment units (fig. 1) was commercially thinned by Galloway Lumber Co. Ltd. to a uniform inter-tree spacing of approximately 4 m, a second was clearcut and the third was left untreated (Mitchell 1994). Stand characteristics are shown in table 1 and the fuel complexes are described in table 2. Sparse understorey vegetation is typical of the lodgepole pine/Oregon grape-pinegrass site series of the dry cool Montane Spruce biogeoclimatic subzone (Braumandl and Curran 1992). Various studies at this site have examined the harvest operations and effects on stand and tree growth, wildlife habitat, and forest health (for example, Mitchell 1994; Allen and White 1997; Safranyik and others 1999; Safranyik and others 2004; Whitehead and others 2004; Whitehead and Russo 2005). This paper examines and discusses selected microclimatic parameters that may affect fuel moisture from the project's 13-year database at the Cranbrook site (1993-2005) and fine fuel moisture content measured in the thinned and unthinned stands during the 2005 fire season.

Figure 1—Aerial overview of site with weather station locations represented by letters A (unthinned control), B (thinned to 4 m spacing), and C (clearcut).

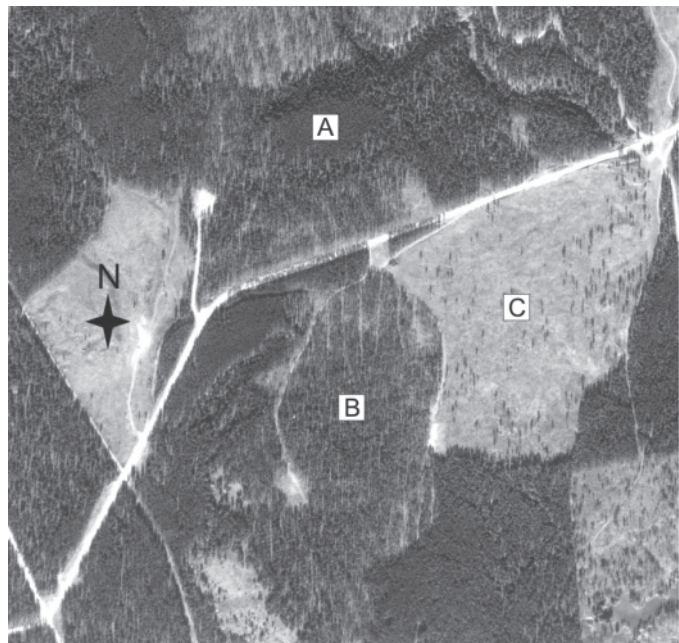


Table 1—Distribution of all trees >7.5 cm d.b.h., by 5 cm diameter classes in the unthinned control and thinned stands at the Cranbrook study site.

Stand	Species	Midpoint of diameter class (cm)						
		10	15	20	25	30	35	40
----- trees/ha -----								
Control	W. Larch	8	0	0	0	0	0	0
	L. Pine	208	700	633	125	17	0	0
Thinned	W. Larch	11	5	5	5	5	5	11
	L. Pine	0	11	155	192	53	5	0

Source: Whitehead, R.J.; Brown, B.N.; Nemec, A.F.L.; Stearns-Smith, S.C. (Submitted 2006). Stand and tree-level growth response to spaced commercial thinning and fertilization treatments in mature lodgepole pine stands in southeastern British Columbia. Natural Resources Canada, Canadian Forest Service, Information Report BC-X---

Table 2—Description of the fuel complexes (July 2005)^a, in the unthinned control and thinned stands at the Cranbrook study site.

Fuel Complex	Control	Thinned
----- Overstory Conifers (7.5+ cm d.b.h.) -----		
Basal area (m ² /ha)	40.0	21.7
Density (live trees/ha)	1692	464
Mean height (m)	20.6	21.8
Mean diameter at breast height (cm)	19.4	23.9
Mean live crown base height (m)	14.0	12.8
Mean dead crown base height (m)	5.0	2.4
Maximum live crown width (m)	2.6	3.6
Canopy bulk density ^b - foliage (kg/m ³)	0.204	0.053
----- Understory Fuels -----		
Understory conifer biomass (kg/m ²)	0.00	0.03
Shrub biomass (kg/m ²)	0.02	0.33
Herbaceous biomass (kg/m ²)	0.03	0.06
Litter biomass (kg/m ²)	0.18	0.18
Litter bulk density (kg/m ³)	19.0	17.1
Litter depth (cm)	0.94	1.06
Duff bulk density (kg/m ³)	113.5	104.9
Duff depth (cm)	2.71	3.22
Dead woody fuels 0.1 to 3 cm in diameter (kg/m ²)	0.15	0.15
Dead woody fuels 3.1 to 7 cm in diameter (kg/m ²)	0.26	0.15
Dead woody fuels 7.1+ cm in diameter (kg/m ²)	0.81	1.95

^aSource: Russo, G.L.; Whitehead, R.J. Natural Resources Canada, Canadian Forest Service, unpublished data.

^bBased on foliar weight calculated using equations from Standish and others (1985).

Methods

Microclimate

Weather stations with dataloggers (Campbell Scientific CR-10) were installed in the centre of each treatment unit (at least 125 m from the outside edge) in 1992 (fig. 1). Air temperature and relative humidity (Campbell Scientific HMP 45C) and full spectrum solar radiation (LiCor LI200SZ pyranometer) sensors were mounted on a tower at 1.3 m height and windspeed monitors (RM Young Wind Monitors) at 3 m height. Three air temperature sensors (Campbell Scientific 107B) were also located nearby at 5 cm above the forest floor. Solar radiation and air temperature sensors at 5 cm height were sampled every five minutes, while air temperature at 1.3 m height, relative humidity and windspeed were sampled every minute. Hourly data summaries and statistics were recorded from May 1 through September 15 from 1993 to 2005. Daily precipitation was measured by a Sierra Misco tipping bucket rain gauge in the clearcut treatment unit only until 2003, when gauges were also added in the thinned and unthinned stands. Each rain gauge was mounted at 1.3 m above ground-level and 3 m to 5 m from the sensor tower.

Weather station and sensor maintenance was carried out as per Spittlehouse (1989). Initial screening of raw data followed procedures described by Meek and Hatfield (1994) which included between-sensor comparisons where sensors were replicated on site (e.g. temperature) and nearby Environment Canada station normals, where sensors were not replicated (relative humidity, windspeed, precipitation and solar radiation). Manual filtering and graphical screening were used to account for sensor drift, and records with missing data for any treatment were deleted from the database before analysis.

Moisture Content of Fine Surface Fuels

Fuel Moisture Sticks—Five sets of 10-hour fuel moisture sticks (4-stick arrays of ponderosa pine dowels weighing 100 g), mounted on wire brackets at 20 cm above the forest floor were positioned 2-m apart on an east-west transect (fig. 2) near the weather station in the thinned and control stands. Each array was weighed on site at 16:00 Mountain Standard Time (MST) on 70 days between June 21 and September 25, 2005, and oven dried at the end of the season to determine how much weight was lost due to weathering effects over the season. Moisture content was calculated on each sampling day using equation 1:

$$\text{Moisture Content (\%)} = 100 \times \left(\frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \right) \quad (1)$$

with dry weights adjusted for weathering, using equation 2:

$$\text{Adjusted Dry Weight (g)} = 100 - \left(\frac{100 - a}{b} \right) \times c \quad (2)$$

where a is dry weight at end of season (grams), b is total number of days exposed, and c is number of days exposed before wet weight was measured.

Needle Litter—Ten 1-m² quadrats, spaced 1 m apart on a transect perpendicular to the moisture stick transect, were established in each stand for collection of lodgepole pine needle litter (fig. 3). Cured lodgepole pine needles were collected from the forest floor nearby and distributed in a thin



Figure 2—Five sets of fuel moisture sticks set up in the thinned stand (left) and in the control stand (right).



Figure 3—Plots for sampling lodgepole pine needle litter in the thinned stand before adding needles (left) and in the control stand after adding needles (right).

even layer (<1.5 cm thick) amongst the quadrats on May 18, 2005 to ensure ample litter for sampling throughout the season. Five samples (approximately 50 g each) of needle litter were collected at 16:00 MST, from alternating odd and even quadrats each sampling day, at 16:00 MST on 70 days between June 21 and September 25, 2005. Each sample was placed in a numbered tin and weighed on site to the nearest 0.1g, then oven dried for at least 24 hours at 100°C and re-weighed. Moisture content of needle litter was calculated using equation 1.

Predicted Moisture Content of Needle Litter—In Canada, the codes and indices that make up the Fire Weather Index System are calculated from weather station outputs. On June 24, 2005, the B.C. Ministry of Forests and Range Southeast Fire Centre installed a standard Fire Weather Station (Forest Technology Systems) in the clearcut opening to determine daily fire weather indices, including the Fine Fuel Moisture Code (FFMC) and Fire Danger Class (B.C. Ministry of Forests 1983). FFMC is a numerical index of the moisture content of litter and other cured fine fuels (Van Wagner 1987). We used FFMC to predict moisture content of lodgepole pine needle litter using equation 3 (Van Wagner 1987):

$$\text{Predicted Moisture Content (\%)} = \frac{147.2 \times (101 - \text{FFMC})}{59.5 + \text{FFMC}} \quad (3)$$

Data Analyses

Microclimate—Mean hourly within-stand windspeed, air temperature, total solar radiation, and relative humidity (RH) during peak fire danger hours (12:00 to 16:00 MST) in the control and thinned stand over thirteen fire seasons (1993 to 2005) were compared graphically. Precipitation data over three fire seasons (2003 to 2005) were consolidated into 54 “rain events” (periods of 1 or more days when precipitation was recorded at one or more stations and separated from other events by at least one day without rain). For each rain event, canopy interception of rainfall in the thinned and unthinned stands was calculated using equation 4 and between-treatment differences were tested with a Wilcoxon signed-ranks test ($\alpha = 0.05$).

$$\text{Interception (\%)} = 100 \times \left(\frac{\text{Rainfall in clearcut (mm)} - \text{Rainfall in stand (mm)}}{\text{Rainfall in Clearcut (mm)}} \right) \quad (4)$$

Fine Fuel Moisture Content—The variance was not constant across the range of moisture content data for fuel moisture sticks and lodgepole pine leaf litter. We grouped the data by Fire Danger Class for graphical comparisons and it was clear that this problem was associated with rainfall, which occurred primarily when the Fire Danger Class was Very Low (26 days). During periods when Fire Danger Class was Low (31 days) or Moderate (12 days) variance in the data was small and consistent. We therefore restricted statistical analyses of between-treatment differences to days with Low or Moderate ratings and used two-tailed paired sample t-tests to investigate between treatment differences in moisture content of fuel moisture sticks ($\alpha = 0.05$) and differences in moisture content of lodgepole pine leaf litter between treatments, and between each treatment and values predicted from FFMC with $\alpha = 0.02$ to approximate an experiment-wise error of 0.05 (Kirk 1968). All statistical analyses were conducted using Analyse-it® for Microsoft Excel.

Results and Discussion

During 54 rain events over three fire seasons, rainfall in the clearcut opening ranged from 0.1 mm in a single day to 99 mm over an 11 day period, and mean canopy interception was significantly lower ($p < 0.0001$) in the thinned stand (51.1 percent; $SE = \pm 2.9254$) than in the unthinned stand (65.3 percent; $SE = \pm 2.9596$ percent).

Mean hourly within-stand windspeed, air temperature, relative humidity and solar radiation in the thinned stand during peak fire hours (12:00 to 16:00 MST) are plotted against the corresponding hourly means in the untreated control stand in figures 4 to 7, respectively. Windspeed and air temperature were consistently higher in the thinned stand. Although total solar radiation was most often higher in the thinned stand, between-treatment differences were not as consistent as for windspeed and air temperature. This may have been due to effects of shading from one or more trees at a particular sun angle and location relative to the sensors in different treatments. Most between-treatment differences were intuitive, with the exception of relative humidity, where no difference was detectable within sensor error (± 3 percent) when measured at 1.3 m above the forest floor. However, there was also no between-treatment difference in mean air temperatures measured at 1.3 m height, although they were consistently higher in the thinned stand when measured much closer to the surface fuels of interest (at 5 cm height). We did not measure RH at 5 cm and cannot discount the possibility that it may also differ nearer the forest floor.

Daily mean moisture contents of fuel moisture sticks in the thinned stand are plotted against corresponding daily means in the untreated control stand in figure 8, and within Fire Danger Classes in figure 9. Moisture content was generally lower in the thinned stand than in the unthinned stand, but the magnitude of that difference decreases when moisture content is below

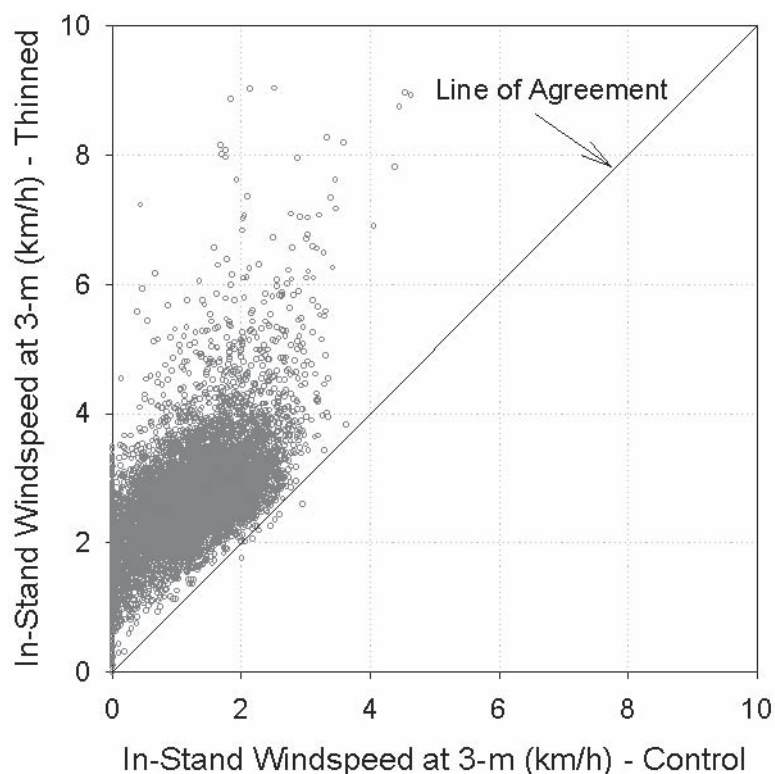


Figure 4—Hourly means of windspeed (km/h) at 3 m height in the thinned stand, measured between 12:00 MST and 16:00 MST, vs. corresponding means in the control stand (n=7380 hours).

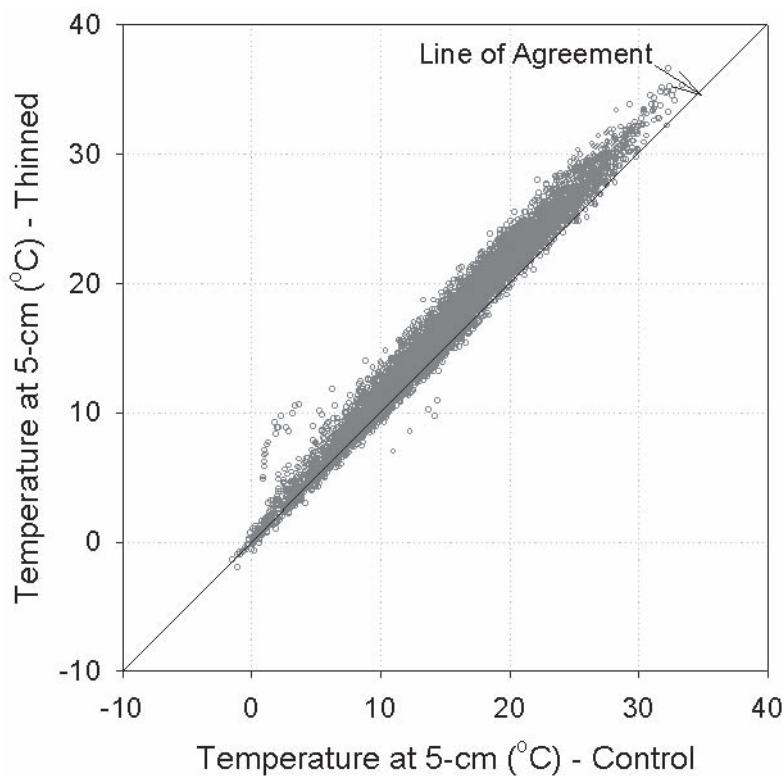


Figure 5—Hourly means of air temperature (°C) at 5 cm height above ground in the thinned stand, measured between 12:00 MST and 16:00 MST, vs. corresponding means in the control stand (n=7760 hours).

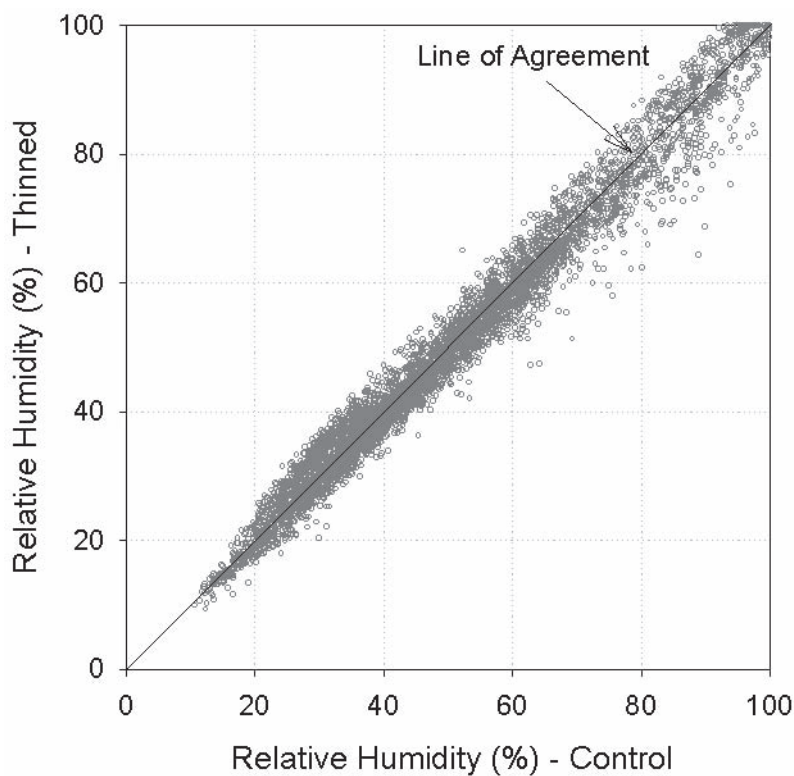


Figure 6—Hourly means of relative humidity (percent) at 1.3 m height in the thinned stand, measured between 12:00 MST and 16:00 MST, vs. corresponding means in the control stand (n=5809 hours).

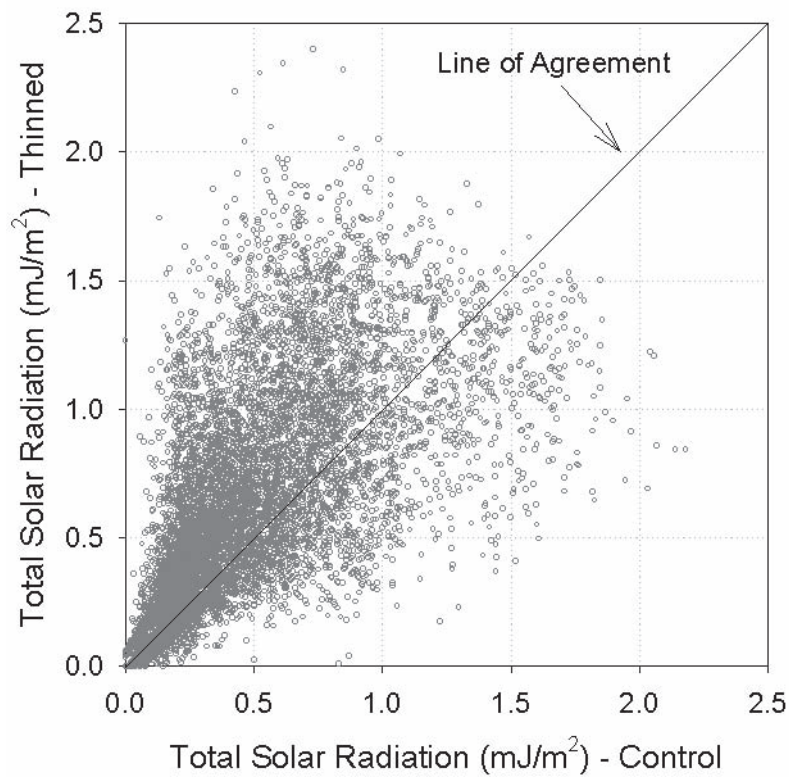


Figure 7—Total hourly solar radiation (mJ/m^2) at 1.3 m height in the thinned stand, measured between 12:00 MST and 16:00 MST, vs. corresponding total hourly solar radiation in the control stand ($n=8503$ hours).

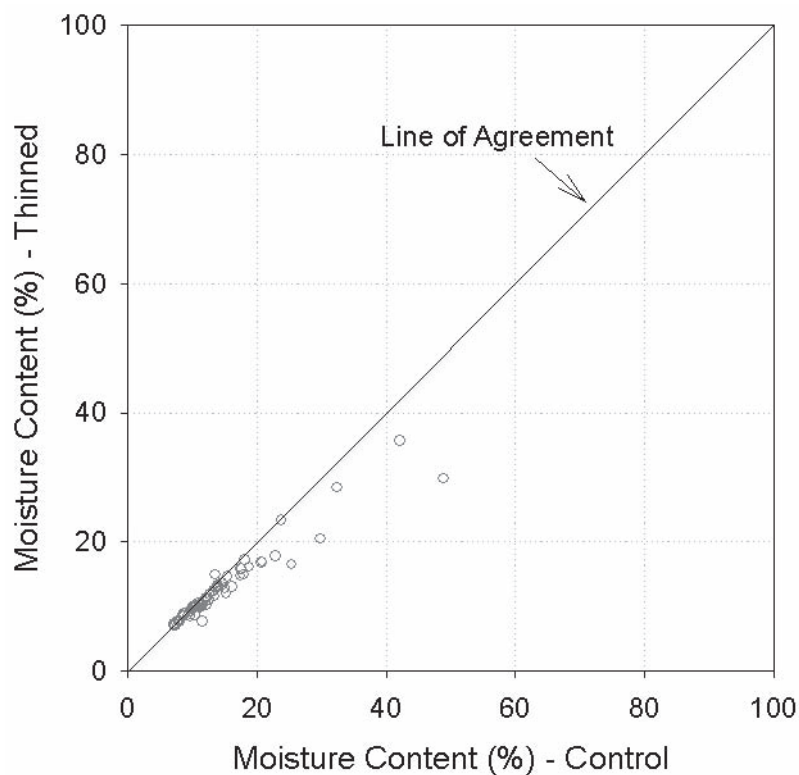


Figure 8—Daily mean moisture content (percent) of fuel moisture sticks at 16:00 MST in thinned and unthinned stands on 70 days between June 21 and September 25, 2005.

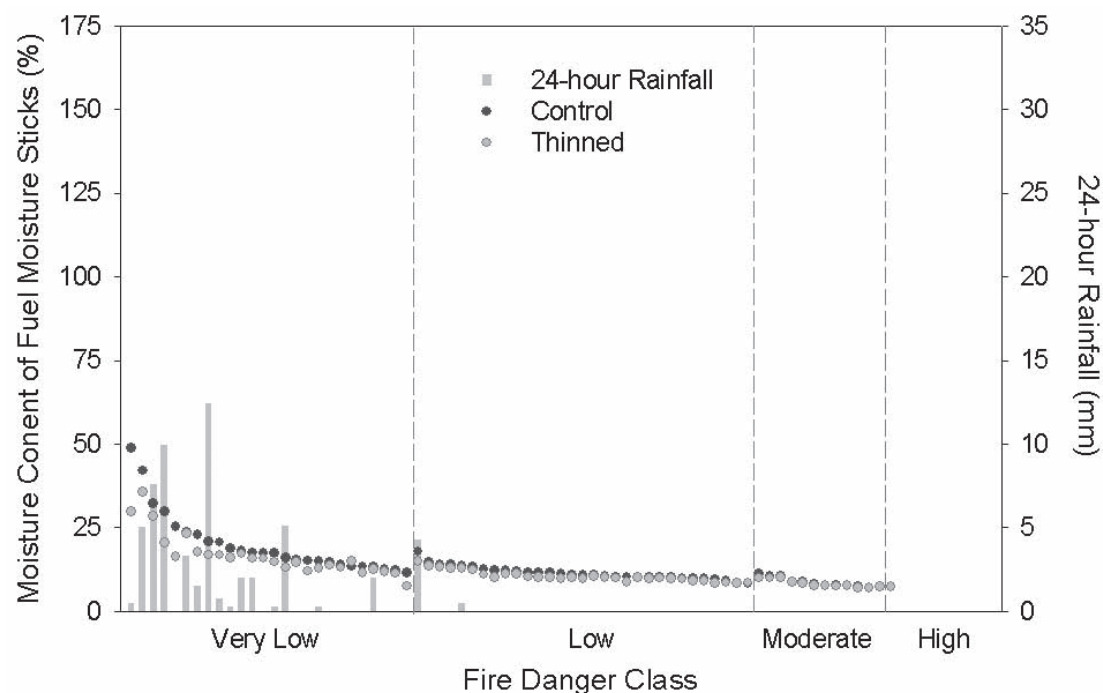


Figure 9—Mean moisture content (percent) of fuel moisture sticks in the thinned and unthinned stands, plotted from wettest to driest control value within different Fire Danger Classes, with corresponding 24-hour rainfall (mm) shown as bars.

about 20 percent and as Fire Danger Class increases (fig. 9; table 3). Variance and between-treatment differences in daily mean moisture contents of needle litter samples were larger than for fuel moisture sticks, but tended to follow the same general trends (fig. 10 and fig. 11; table 3). Pook and Gill (1993) compared an untreated radiata pine (*Pinus radiata* D. Don) stand with one that had been thinned and pruned. They also found that, although litter moisture content was generally higher in the unthinned stand, between-treatment differences decreased with declining moisture content and increasing concern for fire danger.

Table 3—Descriptive statistics (mean, standard deviation and standard error of the mean) for needle litter and fuel moisture stick moisture content at different fire danger classes.

Danger Class		\bar{X}	SD	SE	\bar{X}	SD	SE
		----- litter -----			----- sticks -----		
Low (n=31)	Control	17.2	7.23	1.30	11.4	1.99	0.36
	Thinned	13.2	3.19	0.57	10.5	1.61	0.29
	Predicted	15.7	6.91	1.24	—	—	—
Moderate (n=12)	Control	10.2	2.91	0.84	8.6	1.40	0.40
	Thinned	8.9	2.19	0.63	8.3	1.18	0.34
	Predicted	9.3	1.96	0.57	—	—	—

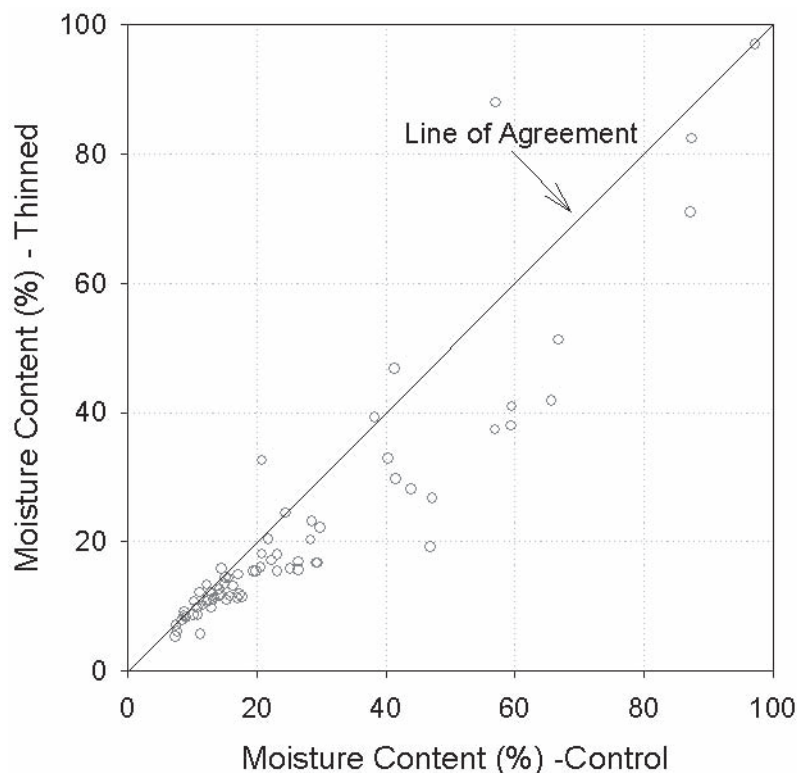


Figure 10—Daily mean moisture content (percent) of lodgepole pine needle litter at 16:00 MST in thinned and unthinned stands on 70 days between June 21 and September 25, 2005.

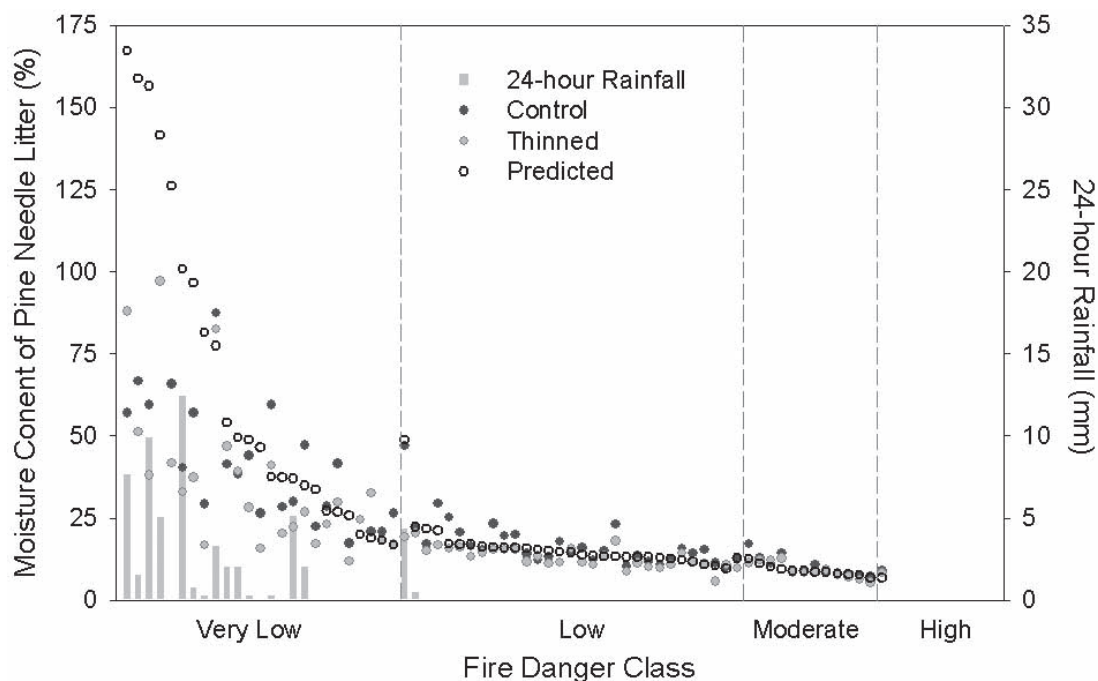


Figure 11—Predicted and actual mean moisture content (percent) of lodgepole pine needle litter in the thinned and unthinned stands, plotted from wettest to driest predicted value within different Fire Danger Classes, with corresponding 24-hour rainfall (mm) shown as bars.

Tanskanen and others (2005) found that canopy characteristics of a mixed Norway spruce (*Picea abies* (L.) Karst) and Scotch pine (*Pinus sylvestris* L.) stand in southern Finland, including canopy depth and leaf area index, correlated strongly with ignition success in surface needle litter. They suggested that differences in surface fuel wetting and drying due to canopy influence on precipitation and wind conditions near the forest floor might have been responsible. Canopy characteristics were quite different in the two lodgepole pine stands we studied (tables 1 and 2), and although we observed a consistent difference in canopy interception of precipitation, windspeed and temperature, the between-treatment differences in moisture content we observed were very small except when fuels were too wet to ignite easily. We found statistically significant between-treatment differences in mean moisture content of both needle litter and fuel moisture sticks when Fire Danger Class was Low, and also for sticks when Danger Class was Moderate (table 4). Although statistically significant, it is unlikely that such small differences in fine surface fuel moisture (for example, 0.3 percent difference in stick moisture content at Moderate fire Danger Class) would have any practical effect on ignition probability or crowning potential. However, there was only one sampling day with a higher fire danger during this study and similar measurements at High and Extreme Fire Danger Classes are recommended to confirm these findings during periods of most concern to fire managers.

Moisture content of fine surface fuels is one important factor used in the Canadian Forest Fire Behaviour Prediction System to model ignition potential (Lawson and others 1994), surface fire intensity and rate of spread (Taylor and others 1997). When combined with stand characteristics, surface fire intensity is used to predict potential for crown fire. The Fine Fuel Moisture Code generated by the Canadian Fire Weather Index System is an index of moisture content of litter and other cured fine fuels, and is used as an indicator of ignition potential or the potential for fires to start and spread (B.C. Ministry of Forests 1983). Our measurements of moisture content of needle litter were not significantly different in either treatment from the values predicted from FPMC using Van Wagner’s equation, when Fire Danger Class was Low or Moderate, although the values were consistently slightly higher than predicted in the control stand and slightly lower than predicted in the thinned stand (fig. 11; table 3). Predictions of moisture content of needle litter from daily FPMC values improved as fire danger increased (fig. 11) and moisture content was predicted well in both stands when Fire Danger Class was Moderate. FPMC reflects fine fuel moisture content across a fairly wide range of stand conditions within a given fuel type and it appears to be robust enough to predict fine fuel moisture content in both stand conditions we studied.

Table 4—Two-tailed p values from paired sample t-tests comparing needle litter moisture content ($\alpha = 0.02$) and fuel moisture stick moisture content ($\alpha = 0.05$).

Danger Class	Control vs. Thinned	Control vs. Predicted	Thinned vs. Predicted	Control vs. Thinned
	----- litter -----			-- sticks--
Low	0.0003	0.0278	0.0224	<0.0001
Moderate	0.0281	0.0391	0.3021	0.0112

Conclusions

Removing approximately half of the basal area of a mature stand of lodgepole pine in southeastern British Columbia, by thinning from below to uniform 4 m inter-tree spacing, resulted in decreased canopy interception of rainfall and increased within-stand solar radiation, windspeed, and near-surface air temperature. Moisture content of both needle litter and of fuel moisture sticks were most different in thinned and unthinned stands following rainfall, but these differences decreased rapidly as fuels dried. Under moderate fire danger conditions, between-treatment differences were very small and not practically significant. Values for moisture content of lodgepole pine needle litter in both stands were predicted well by the Canadian Fire Weather Index System. Further work is needed to examine physical models of fuel moisture and microclimate under a wider range of stand densities, fuel types and climatic conditions.

Acknowledgments

We would like to thank the B.C. Ministry of Forests and Range (BC-MOFR), Protection Branch, Fuel Management Section and the Government of Canada Mountain Pine Beetle Initiative for funding this work; BCMOFR Southeast Fire Centre for assistance with measuring Fire Weather in 2005; John Vallentgoed of the Canadian Forest Service and Jack Selman and Assoc. of Cranbrook B.C. for fieldwork; and, Dr. Nathalie Lavoie (BCMOFR) and Dr. Michael Feller (University of British Columbia) for prompt and helpful reviews of this manuscript. We also wish to acknowledge our former colleague, Bruce D. Lawson for first recognizing the opportunity to do this study.

References

- Allen, E.; White, T. 1997. Decay associated with logging injuries in western larch, *Larix occidentalis*, and in lodgepole pine, *Pinus contorta*. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. Technology Transfer Note 07.
- Braumandl, T. F.; Curran, M. P. 1992. A field guide for site identification and interpretation for the Nelson Forest Region. B.C. Ministry of Forests, Land Management Handbook No. 20. 311 p.
- B.C. Ministry of Forests. 1983. Fire weather indices – decision aids for forest operations in British Columbia. Forest Protection Handbook 12. British Columbia Ministry of Forests, Protection Branch. Victoria, BC.
- Forestry Canada. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Canadian Forest Service Information Report ST-X-3. 63 p.
- Hirsch, K. G.; Pengelly, I. 1999. Fuel reduction in lodgepole pine stands in Banff National Park. In Neuenschwander, L. F.; Ryan, K. C., editors. Proceedings of joint fire science conference and workshop. June 15-17, 1999; Boise, ID. Boise: University of Idaho and International Association of Wildland Fire: 251-256.
- Kirk, R. E. 1968. Experimental Design: procedures for the behavioural sciences. Brook/Cole Publishing Company, Belmont, California. 577 p.

- Lawson, B. D.; Armitage, O. B.; Dalrymple, G. N. 1994. Ignition probabilities for simulated people-caused fires in British Columbia's lodgepole pine and white spruce-subalpine fir forests. Pages 493—505 in Proceedings of the 12th conference on fire and forest meteorology, October 26-28, 1993, Jekyll Island, GA, USA. Society of American Foresters, Bethesda, MD.
- Meek, D. W.; Hatfield, J. L. 1994. Data quality checking for single station meteorological databases. *Agricultural and Forest Meteorology* 69:85–109.
- Mitchell, J. L. 1994. Commercial thinning of mature lodgepole pine to reduce susceptibility to mountain pine beetle. Forest Engineering Research Institute of Canada Special Report SR-94. 19 p.
- Pook, E. W.; Gill, A. M. 1993. Variation in live and dead fine fuel moisture in *Pinus radiata* plantations of the Australian Capital Territory. *International Journal of Wildland fire* 3(3): 155-168.
- Rothermel, R. C. 1983. How to predict the spread and intensity of forest and range fires. General Technical Report INT-143. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 161 p.
- Safranyik, L.; Shore, T. L.; Linton, D. A. 1999. Attack by bark beetles (*Coleoptera: Scolytidae*) following spacing of mature lodgepole pine (*Pinaceae*) stands. *Canadian Entomologist* 131: 671-685.
- Safranyik, L.; Shore, T. L.; Carroll, A. L.; Linton, D. A. 2004. Bark beetle (*Coleoptera: scolytidae*) diversity in spaced and unmanaged mature lodgepole pine (*Pinaceae*) in southeastern British Columbia. *Forest Ecology and Management* 200: 23-38.
- Scott, J. H. 1998. Sensitivity analysis of a method for assessing crown fire hazard in the Northern Rocky Mountains, USA. In: Viegas, D. X., ed.; III International conference on forest fire research; 14th conference on fire and forest meteorology; 1998 November 16–20; Luso, Portugal. Proc. Coimbra, Portugal: ADAI. Volume II: 2517–2532.
- Scott, J. H.; Reinhardt, E. D. 2001. Assessing crown fire potential by linking models of surface and crown fire behaviour. USDA Forest Service Rocky Mountain Research Station Research Paper RMRS-RP-29. 59 p.
- Spittlehouse D.L. 1989. Using dataloggers in the field. Forestry Canada - B.C. Ministry of Forests, FRDA Report No. 086. 49 pp.
- Tanskanen, H.; Venäläinen, A.; Puttonen, P.; Granstöm. 2005. Impact of stand structure on surface fire ignition potential in *Picea abies* and *Pinus sylvestris* forests in southern Finland. *Canadian Journal of Forest Research* 35(2): 410-420.
- Taylor, S. W.; Pike, R. G.; Alexander, M. E. 1997. Field guide to the Canadian Forest Fire Behavior Prediction (FBP) System. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Special Report 11. 60 p.
- Van Wagner, C. E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service, Ottawa, Ontario. Forestry Technical Report 35. 37 p.
- Whitehead, R. J.; Russo, G. L. 2005. "Beetle-proofed" lodgepole pine stands in interior British Columbia have less damage from mountain pine beetle. Natural Resources Canada, Canadian Forest Service, Victoria, B.C. Information Report BC-X-402. 17 p.
- Whitehead, R. J.; Safranyik, L.; Russo, G. L.; Shore, T. L.; Carroll, A. L. 2004. Silviculture to reduce landscape and stand susceptibility to the mountain pine beetle. Pages 233-244. In T. L. Shore, J. E. Brooks and J.E. Stone, editors. Mountain pine beetle symposium: challenges and solutions. October 30-31, 2003. Kelowna, British Columbia. Natural Resources Canada, Canadian Forest Service, Victoria, B.C. Information Report BC-X-399.

Predicting Ground Fire Ignition Potential in Aspen Communities

S. G. Otway¹, E. W. Bork², K. R. Anderson³, and M. E. Alexander⁴

Abstract—Fire is one of the key disturbances affecting aspen (*Populus tremuloides* Michx.) forest ecosystems within western Canadian wildlands, including Elk Island National Park. Prescribed fire use is a tool available to modify aspen forests, yet clearly understanding its potential impact is necessary to successfully manage this disturbance.

Undesirable social consequences of severe, deep burning ground fires include smoke generation and impaired vegetation re-growth. Data on the soil and duff moisture conditions under which ground or subsurface fires may start in aspen are presented, as well as experimental test fire results. Different topographic positions, plant communities and seasons were factored into the research design. The Duff Moisture Code and Drought Code components of the Canadian Forest Fire Weather Index System were calculated and factors including duff moisture content, bulk density and inorganic content measured at the time of ignition. Probability of sustained smouldering ignition models were developed for the aspen forest fuel type, with values of 27 for DMC and 300 for DC at the 50% probability of ignition level. This information will improve the capability to effectively manage aspen using fire in central Alberta.

Introduction

The Duff Moisture Code (DMC) and Drought Code (DC) within the Canadian Forest Fire Weather Index (FWI) System (Canadian Forest Service 1984; Van Wagner 1987) are values of great assistance to fire managers in assessing forest fuel dryness and associated fire risk. Both DMC and DC represent soil duff (i.e. LFH) moisture dryness (Van Wagner 1987), and therefore, its potential to influence fire behaviour. Changes in DMC track moisture in the shallow duff or fibric soil horizon (F-layer), while the DC tracks the humus (H) or deep duff layers as well as heavy downed woody materials. Both indices are determined at noon (standard time) each day during April to October from the standardized weather readings of dry-bulb temperature, 10 m open wind speed, relative humidity and 24 h accumulated precipitation (Turner and Lawson 1978).

Currently there are empirical models correlating the probability of smouldering combustion or ignition and DMC-DC values for select boreal forest types using commercial peat moss as a fuel source (Frandsen 1987, 1991, 1997; Hartford 1989; Lawson and others 1997), but none for trembling aspen. EINP is dominated by trembling aspen (*Populus tremuloides* Michx.) forest. Although these communities may not burn as readily as other boreal forests in the Boreal region (Peterson and Peterson 1992), ground fire may persist in this vegetation under dry conditions for extended periods (Lawson and Dalrymple 1996).

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 2006 28-30 March; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

¹ Manager Resource Conservation, Parks Canada, Elk Island National Park, Fort Saskatchewan, AB, Canada. steve.otway@pc.gc.ca.

² Associate Professor, Range Management, University of Alberta, Department of Agricultural, Food, and Nutritional Science, 410E AgFor Centre, Canada.

³ Fire Behaviour Researcher, Canadian Forest Service, Northern Forestry Centre, Edmonton, AB, Canada.

⁴ Senior Fire Behaviour Research Officer, Forest Engineering Research Institute of Canada, Wildland Fire Operations Research Group, Hinton, AB, Canada. Present address: Canadian Forest Service, Northern Forestry Centre, Edmonton, AB.

In this study, the probability of sustained combustion or ignition was examined for soil duff layers in aspen forests of Elk Island National Park, with ignition tests conducted *in-situ*, as per the Lawson and others (1997) field trials. We also determined whether the indices of modeled DMC-DC predict ignition in aspen forest equal to that of duff moisture, with or without soil bulk density and inorganic content considerations.

Materials and Methods

Study Area

EINP is situated 35 km east of Edmonton in central Alberta (approximate Lat. 53° N; Long. 112° E), at the north end of the Beaver Hills, a post-glacial dead-ice moraine elevated 10 to 30 m above the surrounding plains, sufficient to place the area within the Lower Boreal Mixedwood ecoregion (Strong and Leggat 1991). The dominant vegetation of uplands in the Park is trembling aspen, although open grasslands, shrublands, and white spruce [*Picea glauca* (Moench) Voss] forests are interspersed throughout the area (Polster and Watson 1979). Six different aspen plant community types have been identified within the Park (Best and Bork 2004).

The climate of the area is cool-continental, with long, cold winters and short, warm summers (Bowser and others 1962). Annual precipitation over the last 44 yrs at the Edmonton International Airport indicates an average yearly rainfall of 460 mm (Parks Canada 2004). Precipitation in the Park from April to October, inclusive, accounts for 81% of yearly totals (Parks Canada 2004), and has ranged from 220 to 470 mm over the last 10 yrs (Parks Canada 2004). Mean growing season temperatures vary between 5°C in April to 17°C in summer (Rogeanu 2004), while the frost-free period is about 100 days (Crown 1977).

Both DMC and DC are re-calibrated annually beginning at 'start-up', either 3 days after snow loss in spring or 3 days after a recorded noon temperature of 12°C (Alexander 1983; Canadian Forestry Service 1984), and are continually updated throughout the fire season until October 31st (Turner and Lawson 1978).

Experimental Approach

The approach used in this study was to develop and test empirical relationships between DMC-DC and ignition trials from various sites throughout the Park. A main calibration site was utilized, involving intensive, repeated sampling and testing to establish a detailed profile of burning success under various DMC-DC levels. Sampling was performed both within *in-situ* soils as found within each plot, as well as within 'rainfall exclusion' treatment areas, designed to exclude precipitation and simulate drought (Van Wagner 1970). Exclusion areas were 3 x 3 m, and tarped 1 m above ground to eliminate soil moisture recharge and to ensure low moisture levels (and high FWI values) were represented in at least a portion of the plots where test fires were conducted. Following initial calibration of codes to the primary ignition plots, relationships between ignition and DMC-DC were subsequently tested on independent replicated plots within each of three main aspen plant community types found throughout EINP (Best and Bork 2004).

Field Sampling

All plots were 20 x 20 m in size and permanently marked. The calibration area was situated within a plant community type encompassing traits similar to the two most prevalent types previously documented within EINP, accounting for approximately 70% of all aspen communities previously investigated within the Park. On average, there were two ignition tests within each plot on each day of sampling. Twelve validation plots were randomly selected from a series of 96 vegetation permanent sample plots (PSP) situated on forested uplands throughout EINP.

Daily fire weather observations were obtained from the Environment Canada (Campbell Scientific) automated weather station, 800 m from the calibration site. Precipitation was also measured locally within and adjacent to the calibration site and at each validation site using a manual rain gauge. Unique fire weather indices (DMC-DC) were calculated for each site using localized precipitation and all other observations were from the weather station.

Ignition Testing and Analysis

Most tests took place during the months of May to August 2004, on a schedule frequent enough to coincide with small increases in DMC-DC and to ensure a series of ignitions ranging from 0 to 100% success at each site. Ignition trials were conducted similar to the method used by Lawson and others (1997). Core samples were taken in each plot as per Nalder and Wein (1998), using a cordless drill and hollow, cylindrical tube auger, 5 cm in diameter. Extracted core samples were separated into 2-cm increments and later oven-dried to determine the moisture content and bulk density of each layer. Core holes from moisture sampling were then filled with smouldering peat moss, obtained from commercial supplies. Peat was heated until approximately $\frac{2}{3}$ black in colour and actively smouldering, producing greyish-black smoke. The 5-cm diameter and 12- to 15-cm deep hole generally required about 500 ml of peat moss. Heated moss was carefully placed into the hole, with slight overfilling to compensate for the eventual collapse of peat moss during combustion. Test holes typically smoked for 2 to 5 min until a grey ash cover formed.

After 2 h had passed, the peat was carefully removed, making sure not to scrape the sides of the drill hole at the combustion interface. Bare fingers were used to promptly test the perimeter of the hole throughout the 2- to 4-cm and 4- to 6-cm layers for evidence of persistent ignition. The proportion of the cylindrical core found smouldering corresponded to the reported percentage of success or probability of ignition, to the nearest 10%.

All extracted soil core samples were measured for duff moisture and bulk density using the procedure of Lawson and Dalrymple (1996). A representative number of soil core samples were retained for inorganic content determination, following the methods of Kalra and Maynard (1991). A total of 117 trials were carried out, with 64 on the calibration site and 53 on the validation sites. In most areas the 'burning window', ranging from 0% to 100% success, was duplicated at least twice.

Data Analysis

The variables utilized in all analyses included DMC-DC, moisture content (% oven-dry weight basis), bulk density (kg m^{-3}), and soil inorganic content

(ash, reported as %). To arrive at one model comparing the probability of ignition success versus the corresponding observed DMC-DC, a non-linear procedure, PROC NLIN (SAS 2001), was used and fitted to a logistic model.

The first analysis involved comparing the probability of ignition versus the DMC or DC only on the calibration plots. Coefficients derived from initialization were run on SAS to check for convergence and derive the B_0 and B_1 values of the estimates. The B_0 and B_1 parameters from SAS were then inserted into a simple non-linear regression model. The standard formula used was:

$$P = \exp(B_0 + B_1 * \text{Code}) / (1 + \exp(B_0 + B_1 * \text{Code})), \quad (1)$$

where 'Code' represents DMC-DC, B_0 the intercept and B_1 designates the slope of the regression coefficients. To confirm the relative accuracy of the calibration equations generated, a linear regression analysis was used to determine the goodness of fit (R^2) and other statistical parameters of the models in relation to the actual probabilities observed.

The second analysis included development of a multivariate non-linear regression model, which included DMC-DC, bulk density (ρ_B) and soil inorganic content (Ash), using the following formula, after Lawson and others (1997):

$$P = \exp(B_0 + B_1 * \text{Code} + B_2 * \text{Ash} + B_3 * \rho_B) / (1 + \exp(B_0 + B_1 * \text{Code} + B_2 * \text{Ash} + B_3 * \rho_B)) \quad (2)$$

where 'Code' represents DMC-DC, B_0 the intercept and B_1 , B_2 and B_3 designates the slopes as regression coefficients. For the multivariate non-linear regression analysis, the simple equation coefficients B_0 and B_1 were utilized as a starting point, and when combined with the average inorganic content and actual bulk density measurements, as per Lawson and others (1997), used to initialize the approximate B_2 and B_3 coefficients. Only the DMC or DC value was changed at any one time to form the new multivariate models that were checked against the results of the field trial ignition probabilities. Next, these approximate coefficients were inserted into SAS (SAS 2001) along with the actual data set of varying bulk density values and different average inorganic values from 2003 and 2004. Finally, the derived coefficients were run once more with the average bulk density and inorganic values in the multivariate non-linear regression model run with SAS. Multivariate equations were also assessed for goodness of fit (R^2) and other statistical parameters through linear regression with the actual ignition probabilities measured.

The 53 validation site trials were subsequently tested against the calibration models by comparing actual validation ignition success rates (probability values) against the predicted results expected from the simple non-linear calibration models. Testing involved the evaluation of goodness-of-fit (R^2) and other statistical parameters obtained through the use of linear regression with PROC REG (SAS 2001).

Both the calculated moisture content and corresponding DMC-DC values were compared against observed ignition trial results through linear regression with PROC REG (SAS 2001) to determine any differences between predictive capabilities. Finally, results were compared to modelled ignition probabilities from Lawson and others (1997), utilizing the results modelled at the 50% probability level, as suggested by Cruz and others (2003).

Results

Calibration Results

Results of the ignition analysis generated from the calibration site data are provided in table 1, and indicate that both the simple and multivariate models for both the DMC and DC layers were highly significant ($P < 0.0001$). However, overall R^2 values were greater, and root mean square error (RMSE) and coefficient of variation (CV) values less for models generated using the DMC layer compared to results for the DC (table 2). While the simple and multivariate models resulted in similar R^2 , RMSE and CV within the DMC data, the simple model resulted in a greater R^2 and lower CV than the multivariate model within the DC data (table 1).

Final coefficients for both the simple and multivariate models in the DMC and DC are shown in table 2. Simple and multivariate non-linear models were additionally compared graphically within each of the DMC and DC (fig. 1). Results indicate that the simple model predicted a slightly greater probability of ignition than the multivariate model at a given DMC-DC code, although this difference was more apparent within the DC data (fig. 1). This finding indicates the addition of soil bulk density and inorganic content to the model tended to reduce the anticipated probability of ignition. For example, the simple model indicated a 50% probability of ignition at DMC and DC values of 27 and 300, respectively (fig. 1). In contrast, DMC and DC codes resulting in the same ignition, but using the multivariate model, were 29 and 336. Given that the results from either model were similar, and because

Table 1—Linear analysis of calibration site DMC and DC values, and observed probability of ignitions using simple or multiple regression modelled equations, showing goodness of fit (R^2), root mean square error (RMSE), coefficient of variation (CV) and probability ($Pr > F$).

Code	Model Type	Linear Analysis			
		R^2	RMSE	CV	$Pr > F$
DMC	Simple Equation	0.74	0.14	16.69	<.0001
	Multiple Equation	0.74	0.15	18.72	<.0001
DC	Simple Equation	0.54	0.23	50.42	<.0001
	Multiple Equation	0.43	0.24	80.93	<.0001

Table 2—Coefficient parameters and standard errors for simple and multiple non-linear models comparing DMC and DC values to the probability of ignition in the aspen fuel type at EINP.

Code	Model Type	B0	SE ^a	B1	SE	B2	SE	B3	SE	F	$Pr > F$
DMC	Simple ^b	-3.11	0.63	0.12	0.02	—	—	—	—	1008.31	<.0001
	Multiple ^c	2.92	1.38	0.12	0.02	-0.16	0.05	-0.002	0.001	485.68	<.0001
DC	Simple	-8.96	2.22	0.03	0.01	—	—	—	—	147.14	<.0001
	Multiple	7.98	3.03	0.04	0.01	-0.36	0.08	0.0002	0.001	127.55	<.0001

^a Standard error.

^b Simple non-linear equation is $P = \exp(B0 + B1 \cdot \text{Code}) / (1 + \exp(B0 + B1 \cdot \text{Code}))$.

^c Multivariate equation is $P = \exp(B0 + B1 \cdot \text{Code} + B2 \cdot \text{Ash} + B3 \cdot \text{pB}) / (1 + \exp(B0 + B1 \cdot \text{Code} + B2 \cdot \text{Ash} + B3 \cdot \text{pB}))$.

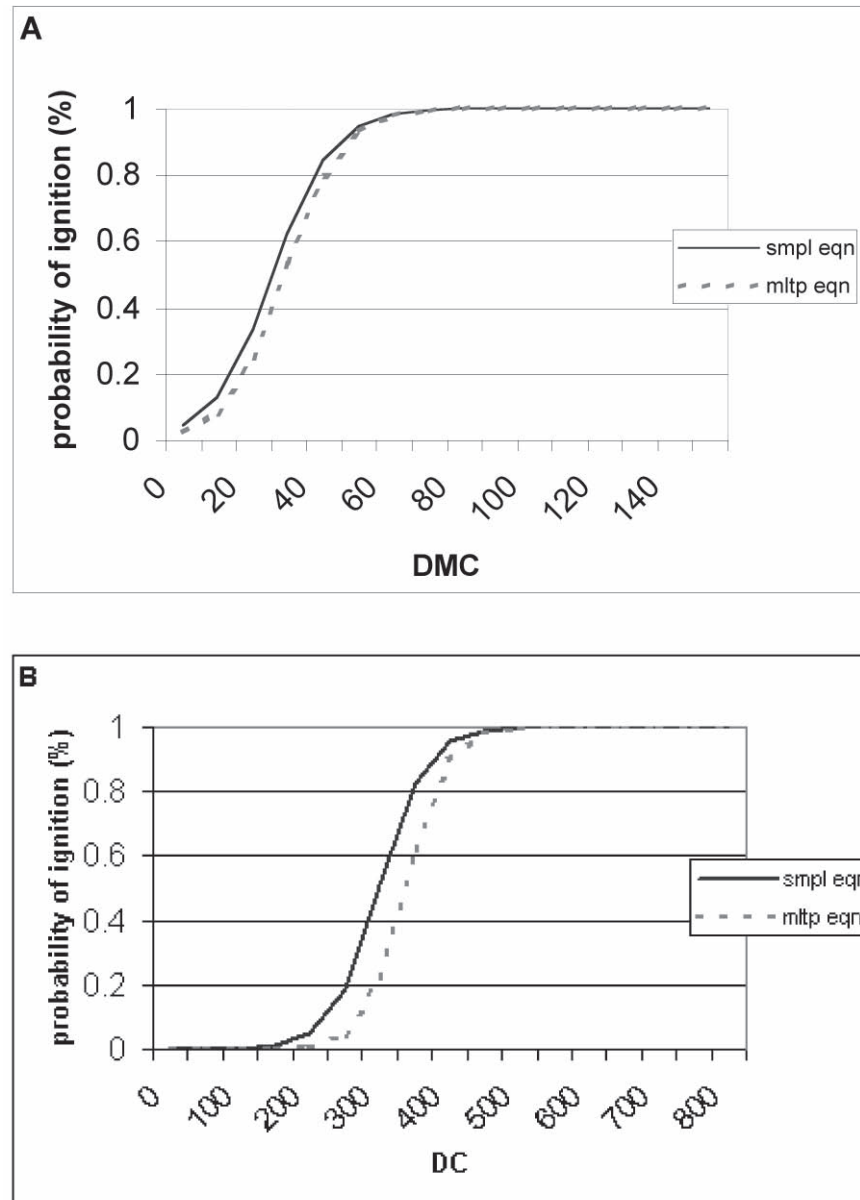


Figure 1—Results of the non-linear analysis fitted to a logistic model showing the probability of sustained ignition against the DMC (A) and DC (B) for simple (smpl) and multivariate (mltp) equations.

inorganic soil data were limited, the simple models were chosen for subsequent application to the validation data.

Validation of Ignition Prediction Models

Ignition probability values observed at the validation trials were compared directly to the values predicted using the simple model developed from the calibration site for both DMC and DC layers. For the DMC, a strong relationship ($P \leq 0.001$) was evident between observed and predicted ignition, but only at the Beaver and Tawayik sites (table 3), with no relationship ($P = 0.52$) at the Goose site. Goodness-of-fit comparisons for the former two were

Table 3—Comparison of the validation observed field burning data to the calibration site modelled results using simple linear regression, showing goodness of fit (R^2), root mean square error (RMSE), coefficient of variation (CV) and probability ($Pr>F$).

Code	Validation Site	Linear Analysis			
		R^2	RMSE	CV	$Pr>F$
DMC	Beaver	0.49	0.20	31.12	0.0006
	Goose	0.04	0.26	34.67	0.5216
	Tawayik	0.46	0.23	33.85	0.0013
DC	Beaver	0.50	0.11	78.05	0.0004
	Goose	0.54	0.22	49.84	0.0029
	Tawayik	0.33	0.23	80.79	0.0102

relatively strong ($R^2 = 0.46$ to 0.49), with a positive relationship between predicted and observed ignitions (table 3). Results of the DC analysis were similar to DMC, except that a significant relationship ($P \leq 0.01$) was evident between actual and observed ignition at all three validation sites (table 3). Goodness-of-fit values for the three sites were similar ($R^2 = 0.33$ to 0.54) to those observed previously with the DMC.

Comparison of Moisture Content and FWI System Fuel Moisture Codes on Ignition Success

Regressions of ignition success with either moisture content or DMC-DC were compared for each soil layer (table 4). Results from the calibration site and the total pooled data from all validation sites were analysed for both F and H-layers. In all comparisons except the calibration F-layer, FWI values of DMC-DC were superior predictors of ignition than soil duff moisture. FWI values had a higher goodness-of-fit ($R^2 = 0.20$ to 0.53) and lower RMSE (23 to 35) and CV (27 to 89%) than moisture content comparisons. All FWI comparisons were significant ($P < 0.001$).

Table 4—Comparison of observed ignition success versus either moisture content (MC) or the FWI codes of DMC/DC, showing goodness-of-fit (R^2), root mean square error (RMSE), coefficient of variation (CV) and probability ($Pr>F$) for the calibration site (Allcal) and combined validation data (Allval).

Soil Layer	Parameter	Linear Analysis			
		R^2	RMSE	CV	$Pr>F$
F-layer	Allcal MC	0.62	18.94	22.42	<.0001
	Allcal DMC	0.44	23.02	27.26	<.0001
	Allval MC	0.02	33.68	40.00	0.2899
	Allval DMC	0.20	30.37	36.06	0.0007
H-layer	Allcal MC	0.25	40.32	74.47	<.0001
	Allcal DC	0.53	31.98	59.07	<.0001
	Allval MC	0.07	44.14	110.35	0.0570
	Allval DC	0.40	35.45	88.63	<.0001

Comparison of Results to Other Models

Comparison of the modeled values derived here to Lawson and others (1997) indicate the ignition results from EINP were associated with lower DMC-DC values relative to similar ignition probabilities in boreal forest duff types elsewhere. At the 50% probability of ignition, Lawson and others (1997) calculated DMC values between 39 and 58 in upper feather moss and upper sphagnum moss vegetation. Using the lower feather moss fuel type, the Lawson and others (1997) DC value at the 50% probability was 482. In Anderson (2000), the 50% probability of ignition for the DMC layer in the D-1 (leafless aspen) fuel type was calculated near 79, although the logistic regression model utilized in that study was from Hartford (1990).

Discussion

Using the simple ignition models developed in this study, code values of 27 and 300 for DMC and DC, respectively, were determined to approximate the 50% probability of ignition. Incorporating inorganic content and bulk density into multivariate predictive models led to minimal changes in threshold code values (DMC 29 and DC 336 for 50% probability). The addition of physical fuel properties only marginally improved the predictability of ignition models. Both Frandsen (1987) and Lawson and others (1997) developed multivariate equation models for certain duff types; however, neither definitively compared the accuracy of simple and multivariate models. Ignition tests in these studies were also recorded as binary events (yes or no), whereas in the current study a range of probabilities were recorded to a finer resolution (0.0 to 1.0).

Model goodness-of-fit values based on comparison of the validation to calibration data indicated ground fire occurrence could be predicted to some degree from calibrated ignition models. Variation in model accuracy may be explained by the shallow nature of the surface duff profile and substantial inorganic content and bulk density values found in duff layers of the Park.

Validation ignition models for the DC layers, while significant, were found to have a lower R^2 and higher CV than those for the DMC. The shallow depth of the DC layer, coupled with a high inorganic content may explain these observations.

Ignition was under-estimated by calibration models on average at actual ignition levels over 60% for DMC and 20% for DC. Ignition success in the field often increased from less than 20% to over 50% and above, over a very short time interval (days). Ignition also appeared to change rapidly with moisture depletion and changing FWI codes. As a result, effective modelling of ignition remains difficult under rapidly changing environmental conditions, in turn affecting the accuracy of ignition models.

The smouldering threshold (i.e. 50% probability of ignition) for the DMC and DC in ignition trials of Lawson and others (1997) were much greater than that observed in the current study. Lawson and others (1997) also found that a narrow range of moisture separated successful from unsuccessful ignitions, particularly in white spruce duff, somewhat similar to observations within the current study where ignition increased from 20% to more than 50% over a few days.

Conclusions

This research established and tested non-linear models relating DMC and DC to the probability of duff ignition, or ground fire. Overall, simple rather than complex multivariate models were more effective in relating DMC and DC to ignition. During the validation procedure, models developed for the independent calibration site were relatively effective at detecting a change in ignition, although the accuracy of those models remained quite low.

Results of this study indicate that the aspen forest and D-1 fuel type of EINP is quite unique in its properties. Thus, the results of this study are not directly comparable to either that of Frandsen (1987) or Lawson and others (1997) in conifer vegetation types.

Acknowledgments

The authors wish to thank the management and staff of Elk Island National Park for their patience in allowing this research to be carried out and for their assistance in conducting fieldwork. Duff sampling field assistance was also received from Matthew Cacka and the family of the corresponding author. Support for this study was provided by EINP, the University of Alberta, the Canadian Forest Service and FERIC.

References

- Alexander, M. E. 1983. Overwinter adjustment to spring starting values of the Drought Code. Forest Report No. 28: 5. Edmonton, AB. Canadian Forestry Service, Northern Forest research Centre.
- Best, J. N.; Bork, E. W. 2004. Aspen understory community classification in Elk Island National Park using environmental & overstory characteristics. Parks Canada unpublished manuscript. 59 pp.
- Bowser, W. E.; Kjearsgaard, A. A.; Peters, T. W.; Wells, R. E. 1962. Soil survey of Edmonton: sheet 83-H. Soil Survey Report number 21. Canadian Department of Agriculture, Research Council of Alberta and University of Alberta, Edmonton, Alta.
- Canadian Forestry Service. 1984. Tables for the Canadian Forest Fire Weather Index System, 4th Edition. Canadian Forest Service, Forest Technical Report 25.
- Crown, P. H. 1977. Soil survey of Elk Island National Park. Alberta Institute of Pedology, publication number S-77-38. 128 pp.
- Cruz, M. G.; Alexander, M. E.; Wakimoto, R. H. 2003. Assessing the probability of crown fire initiation based on fire danger indices. *Forestry Chronicle* 79: 976-983.
- Frandsen, W. H. 1987. The influence of moisture and mineral soil on the combustion limits of smouldering forest duff. *Canadian Journal Forest Research*, 17: 1540-1544.
- Frandsen, W. H. 1991. Burning rate of smouldering peat. *Northwest Science*, 65: 166-172.
- Frandsen, W. H. 1997. Ignition probability of organic soils. *Canadian Journal of Forest Research*, 27: 1471-1477.

- Hartford, R. A. 1989. Smouldering combustion limits in peat as influenced by moisture, mineral content, and organic bulk density. Pp. 282-286. In: D.C. MacIver and others (eds.) Proceedings of the 10th Conference on Fire and Forest Meteorology, Forestry Canada, Ottawa, Ont.
- Kalra, Y. P.; Maynard, D. G. 1991. Methods for forest soil and plant analysis. Forestry Canada, Northwest Region, Northwest Forestry Centre, Edmonton, Alberta. Information Report NOR-X-319.
- Lawson, B. D.; Dalrymple, G. N. 1996. Ground-truthing the Drought Code: field verification of overwinter recharge of forest floor moisture. Canadian Forest Service Pacific Forest Centre and B.C. Ministry of Forest Research Branch FRDA Report 268.
- Lawson, B. D.; Frandsen, W. H.; Hawkes, B. C.; Dalrymple, G. N. 1997. Probability of sustained smouldering ignition for some boreal forest duff types. Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Forest Management Notes, 63.
- Nalder, I. A.; Wein, R. W. 1998. A new forest floor corer for rapid sampling, minimal disturbance and adequate precision. *Silva Fennica* 32: 373-382.
- Parks Canada. 2004. Weather records for Elk Island National Park, 2002 through 2004. Elk Island National Park internal document.
- Peterson, E. B.; Peterson, N. M. 1992. Ecology, management and use of aspen and balsam poplar in the prairie provinces. Forestry Canada, Northern Forestry Centre, Special Report No. 1.
- Polster, D. F.; Watson, L. E. 1979. Vegetation classification and evaluation — Elk Island National Park. Parks Canada Report prepared by Techman Ltd. 134 pp.
- Rogean, M.P. 2004. Historical fire weather review: Edmonton Region. Strathcona County, Phase II Firesmart Initiative. 19 pp.
- SAS Institute Inc. 2001. The SAS system for windows. Release 8.02. Cary, N.C.
- Strong, W. L.; Leggat, K. R. 1991. Ecoregions of Alberta. Alberta Forestry, Lands and Wildlife, Land Information Services Division, Resource Information Branch, Edmonton, Alta. 110 pp.
- Turner, J. A.; Lawson, B. D. 1978. Weather in the Canadian Forest Fire Danger Rating System: A user guide to national standards and practices. Canadian Forest Service Information Report, BC-X-177.
- Van Wagner, C. E. 1970. An index to estimate the current moisture content of the forest floor. Canadian Forestry Service Publication 1288. 23 pp.
- Van Wagner, C. E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Forest Technical Report 35. 37 pp.